EVALUATION OF PORE-SIZE DISTRIBUTION OF POROUS MEDIA FROM CAPILLARY PRESSURE CURVES— A NETWORK APPROACH

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the

DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

SEPTEMBER, 1973

CERTIFICATE

It is certified that this work has been carried out under my supervision and has not been submitted elsewhere for a degree.

Date: 3rd September 1973

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ACKNOWLEDGEMENTS

The author is deeply indebted to Dr. A.K. Singhal for his pains-taking efforts and guidance all through the work without which this work could not have been completed in time.

Thanks are also due to our friends for many fruitful discussions which helped in better appreciation of some of the points discussed in this work.

Lastly the author wishes to acknowledge the help rendered by Sri B.S. Pandey in typing the manuscript and Sri D.S. Panesar in preparation of drawings.

Author

CONTENTS

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LIST OF FIGURES

***

LIST OF TABLES

***

ABSTRACT

Porous media are interconnected networks of void space of multitude shapes and sizes. Attempts in developing an analytical expression for the fluid flow behaviour through them have not been satisfactory to-date. The classical model of the bundle of tubes is too simplified a model to be realistic and useful. In the present work the flow behaviour of porous media has been modelled by a network of interconnected tubes of different sizes. An attempt has been made to extend the concept of relating pore-size distribution (both volumetric and number) to the capillary character of the network. The validity of 'ink-bottle' effect has been tested by the comparison of capillary pressure data with the actual tube size distribution of the network.

The extent of inter connection between the pores in a network is found to be a very important factor influencing the shape of the P_c curves. Therefore, any model of porous media based on bundle of tubes concept is likely to give erroneous results. Fatt's model, however, may be used with modified value of the exponent (between -2.5 to -3.5) to give better result for the number distribution. Similarly while correcting the measured pore-size distribution (volumetric) by Meyer's method, it has been found that the relation $V \propto r^{1.5}$ improves the interpretation. These values for exponents have been obtained

for networks with six tubes (on the average) meeting at a node point. The modified values of exponents perhaps correct for inter_connection between the pores.

CHAPTER 1

INTRODUCTION

Porous media, whether in the form of natural rocks or particulate aggregates such as powder-packs, have quite a few interesting properties compared to the properties of their bulk solid phase. One such property, the flow of fluids through them, has been engaging the attention of scientists in many disciplines. The petroleum engineers are interested in knowing the quantity and the maximum possible rate of fluid withdrawal from reservoir rocks. The soil-scientists concern themselves with the distribution and movement of soil-moisture. Chemical engineers, likewise, dealing with the problem of drying, are faced with the question of determining the rate at which the moisture from the pores can move up to the surface. Similarly while analyzing the performance of a packed bed, it is pertinent to evaluate the effectiveness of mass-transfer as well as liquid hold-up. Internal void structure is important in determining the effectiveness of batteries as well as the moisture movement capacity of the concrete and bricks.

The total internal surface area, porosity or permeability do not provide adequate information about the complex pore structure of porous media. Quite often, it is necessary not only to know these cumulative properties but also the distribution of pore sizes. The shapes of the relative permeability

and capillary pressure curves are markedly affected by pore-size distribution. Of the two, relative permeability does not seem to be suitable for determining the pore-size distribution because of the averaging effect associated with the flow phenomena in the whole spectrum of pore-sizes. Capillary pressure, on the other hand, is a unique function of pore-size, interfacial tension and wettability. Keeping the latter two quantities constant it is possible to estimate the sizes and proportions of the contributing pores from the successive higher values of capillary pressure.

Capillary phenomena comes into play whenever a fluid/fluid interface is in contact with a solid surface. Due to unequal interfacial tensions, fluid adjusts itself to attain thermodynamic equilibrium, thereby minimizing surface free energy. The well known Laplace equation which relates the various quantities affecting capillary pressure is

$$P_c = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (1.1)$$

where P_c = Capillary pressure,

γ = Interfacial tension

r_1 & r_2 = Two principal radii of curvature of the surface at any point.

The implicit assumption that the sum of reciprocals of the two principal radii of curvature (mean curvature) is the same at every point on the equilibrium surface, is a

mathematical consequence of the fact that the surface area tends to a minimum (i.e. spherical or nearly so in most cases). All methods of pore-size determination, that make use of capillary pressure are based on the hypothesis that the mean curvature of an equilibrium liquid surface can somehow be related to the pore-size. This relationship is difficult to establish for any shapes other than that with the simplest geometry. For straight cylindrical capillaries, Laplace's equation can be written as

$$P_c = \frac{2\gamma \cos\theta}{r} \qquad (1.2)$$

where θ is the angle of contact of the interface through the wetting phase and r is the radius of the capillary. This equation can correctly predict the pore-sizes and their distribution if bundle of parallel tubes is a valid model for porous media. For real system, this is an obvious over simplification and the equation will relate the capillary pressure to the radius of the largest opening leading to the pore rather than the radius of the pore itself. But in the absence of a better known method this pore entry radius is taken as a measure of the actual pore-size. Implied in this is the assumption that the actual pore-size is some unique function of the pore entry size for pores of all sizes. This however is difficult to justify.

In capillary pressure experiment with porous media, the sample is gradually desaturated of the wetting phase by

injecting some non-wetting fluid (making known contact angle with the solid surface) at successive higher pressure. At equilibrium, the capillary pressure opposing the entry of non-wetting phase, P_c; is balanced by the externally applied pressure. This P_c when put in Eq.(1.2) gives the radius of the smallest pore, r, invaded by the non-wetting phase. Knowing the saturation of the non-wetting phase in the sample at the stage, we arrive at the value of the fractional pore volume contained in the pores with radius greater than or equal to r. By successively increasing P_c, non-wetting phase is forced into smaller and smaller pores and the fractional pore volume corresponding to different values of r can be obtained. This method has been universally used for the calculation of volumetric pore-size distribution in porous media.

For fluid flow calculations, the pore number distribution is the desired quantity. To arrive at the number distribution from volume distribution, it is essential that we make some assumption about the pore-geometry and its dimensions. For parallel tube model of porous media, the quantity in question is the relation between the tube radius and length. Based on the assumption that $l = Cr^{\alpha}$, where C is proportionality constant and r is radius, Fatt[1] derives the number distribution function as follows:

$$f(r_2-r_1) = \frac{\int_{s_1}^{s_2} P_c^{2+\alpha}\, ds}{\int_{0}^{1} P_c^{2+\alpha}\, ds} \qquad (1.3)$$

where $f(r_2-r_1)$ = frequency of occurrence of pores in the interval r_2-r_1

S = saturation of the non-wetting phase

There is considerable disagreement between different workers in the field about the value that α should assume. Whereas Fatt[1] proposes a value of -1. Meyer[2] implicitly takes this as 1. Dallavalle[3] seems to have some experimental results to back his suggestion of the value between 0 and 1. In the absence of a conclusive evidence, this factor still remains uncertain.

The method just discussed is essentially empirical in nature. For quantitative description of flow phenomena in porous media, a functional relation between the pore-size distribution and capillary pressure curve is needed. It will be our endeavour in the present work to examine the existing models and suggest one which can reasonably interpret the experimental P_c vs saturation curves in terms of pore-size distribution.

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CHAPTER 2

LITERATURE REVIEW AND ANALYSIS

Natural porous systems can be viewed as inter-connected network of voids of different shapes and sizes separated by interconnecting links or necks. Often the behaviour of such a system is approximated by a bundle of capillaries[4]. Dullien and Batra[5] have collected a comprehensive list of references of the attempts made in this direction in their review article. It is apparent that very few real porous media will contain pores of the straight cylindrical shapes, and therefore the pore radii calculated from the capillary pressure have to be considered as equivalent pore radii. This is defined as the radius of a straight cylindrical capillary that would give rise to the same capillary pressure as the measured value. Since a variety of different capillary shapes may give rise to the same capillary pressure, the pore dimensions calculated from capillary pressure measurements are at best semi-quantitative. The equation relating properties of porous media to the radius distribution of the equivalent bundle of tubes have been given by a number of authors[6-9]. However, apart from the mathematical simplicity associated, the most glaring weakness of the model is the prediction of highly anisotropic properties. Porous systems on the other hand are known to be isotropic in nature. Inspite of its success in correlating certain properties viz. permeability

formation factor etc., the model has failed to approximate the capillary pressure vs saturation and its hysteresis.

For more complex systems, such as random packing of non-spherical particles, Carman[4] suggests that twice the hydraulic radius is the suitable value of r in the following expression for P_c:

$$P_c = \frac{2\gamma \cos\theta}{r} \qquad (2.1)$$

where the hydraulic radius is defined as the ratio of porosity f to the surface area A in unit bulk volume. A more accurate account of the curvature for different geometry of the capillary is given by Gregg and Sing[10]. On substitution Eq.(2.1) is reduced to

$$P_c = \frac{\gamma \cos\theta A}{f} \qquad (2.2)$$

Substituting the expression for the specific surface area in terms of permeability K and porosity, from the Kozeny[11] equation, Eq.(2.2) becomes

$$\frac{P_T}{\gamma}\left(\frac{K}{f}\right)^{\frac{1}{2}} = \left(\frac{1}{k}\right)^{\frac{1}{2}} \qquad (2.3)$$

where the threshold pressure P_T has been substituted for P_c. k is an empirical textural constant of the medium and accounts for the deviation of a porous system from the model.

This was obviously a gross simplification, and Carman himself points out that, for porous bodies with widely varying pore-size distribution, calculations based on Kozeny-Carman

model can be quite wrong.

Sphere Pack Model:

The earliest attempt in approximating the flow behaviour of porous media was their simulation by packs of uniform spheres. But the complexity of the pore-geometry in sphere-packs prevented the derivation of an accurate and meaningful description of flow behaviour through them. Recognizing the difficulty, Kozeny[11] inductively developed an equation relating permeability to porosity and internal surface area of a sphere-pack.

$$K = \frac{C\, f^3}{T S^2} \qquad (2.4)$$

where f = porosity

T = tortuosity

S = specific surface area

Kozeny equation, as modified by Carman[12] and given as

$$K = \frac{f^3}{k\, S^2 (1-f)^2} \qquad (2.5)$$

did not prove to be of much value, aside from its use in estimation of the surface area of powders.

A comprehensive review of the use of sphere-packs to model the flow behaviour of packed beds, has been given by Haughey and Beveridge[13]. In their analysis, the emphasis has been in arriving at the mean fractional voidage for both regular and random packing, on the basis of the position coordinates and the coordination numbers, rather than the pore -

geometry. Generally speaking, particle shape and size distribution are the two factors most likely to affect the packing structure and its properties. Some work has been carried out on the densest packing of non-spherical particles. But the multiplicity of packing types with the same coordination number and vice versa, accompanied by the size distribution of particles further complicate the pore structure. Hence the task of analytical description is rendered almost hopeless.

The problem of capillary hysteresis in uniform sphere packs was studied by Kruyer[14], Frevel and Kressley[15], Meyer and Stowe[16,17] and more recently, by Melrose[18]. Their analysis points out that the curvature of the invading interface of non-wetting phase is generally larger resulting in higher value of capillary pressure compared to the retracting interface associated with imbibition. This, according to them, may be the reason for the porous media exhibiting capillary hysteresis.

Naar and Wygal[19] view any porous media as a random mixture of spherical particles and propose a model based on the principle of averaging the properties of the basic sets to arrive at the mixture-properties. The problem essentially is finding of appropriate weighting factors to average the basic set properties, determined experimentally. Expressions for porosity, permeability and capillary pressure behaviour of the porous media have been developed. But the experimental support to this model is too meagre to be accepted.

Network Model:

The description of single and multiphase fluid flow through capillary pores in porous media has been unsatisfactory because the pore-geometry is too complex to be described adequately by analytical expression. Markin[20] used a model consisting of a system of randomly arranged intersecting voids with circular cross-section and continuously varying radius. No more than three branches could converge at any point in the net_work. This model, however, does not seem to have gained the favour of the research workers in the field.

Fatt[1] replaced each pore with a cylinder in his two dimensional network with different grid patterns. He could incorporate random assignment of parameters, such as pore-size distribution and number of cylinders meeting at a node point, in the model. Fluid flow in the network could be followed as one pore after another was desaturated.

All of Fatt's calculations were performed assuming a continuous wetting phase in the tubes. As a consequence, no wetting phase could be trapped in a desaturation process. Dodd and Kiel[21] extended this work by applying desaturation steps such that wetting fluid could be trapped. Cylindrical pores were assumed to contain only one fluid at a time; thus allowing the displaced fluid to be trapped if no continuous path to the effluent end was available. Thus at any time the pore could be either full of wetting phase or non-wetting phase.

Singhal[22] modified Fatt's model by providing for the possibilities of different flow regimes in different channels during desaturation process. The four basic flow regimes viz. single phase flow, displacement, annular and slug flow were allowed to occur any where in the model whenever suitable conditions existed. In addition, he substituted triangular capillaries for circular shaped tubes to account for funicular flow regime over extended range of saturation. A trapping factor, evaluated from the comparison of the model with the experimental results, was used to effect trapping of fluid. This model has duplicated the relative permeability behaviour of porous media reasonably well and we propose to use the same model for approximating its capillary pressure vs. saturation behaviour.

Other Model:

Haring and Greenkorn[23] have proposed a parametric statistical model, from the theoretical considerations, to calculate the macroscopic properties such as saturation, permeability and dispersion coefficient in porous media. Porous medium is approximated by a large number of randomly oriented straight, cylindrical pores with randomly varying radius and length. The relationship between saturation and P_c contains two constants which are the parameters of the pore-size distribution function. They maintain that the two parameter incomplete Beta function can adequately represent

most of the pore-size distributions encountered in porous media. Non-uniformity of a medium can be incorporated by adjusting the magnitude of the two parameters in the distribution function. Of all the models proposed to-date this appears to be the most promising for analytical description of flow phenomena as well as mass transfer through porous media.

Paytakes[24] et al, while developing a model for the packed bed, point out some in-consistency in Haring and Greenkorn's model. Whereas in Haring's model the minimum tube size is implicitly assumed as zero, the smallest pore-size in a packed bed is definitely not zero. As a consequence, the average pore diameter calculated from this model are smaller than the smallest pore calculated from sphere pack model. The calculated pore length is about equal to the half the average grain diameter of the pack. However, this minor inconsistency in the model can be removed by substituting for the finite value of the smallest pore-size for packed bed and thereby slightly modifying the model.

In their own model, Paytakes et al assume convergent-divergent circular tubes as the basic units of which a packed bed is assumed to comprise of. These basic units do not have any lateral connection thus allowing fluid flow only in the vertical direction. By introducing convergent-divergent flow channels, they seem to have accounted for inertia effects in

flow path. However, this could not be a realistic approach for porous media where interconnections are quite important in considering the flow behaviour.

2.2 Pore-Size Distribution:

It is obvious that pore-size distribution is very important in describing fluid-flow through porous media. Ritter and Drake[25] proposed a method of determining the pore-size distribution from mercury porosimetry data. The basis of this method is the concept that mercury is forced into gradually smaller pores against capillary forces as the pressure is increased. The fact, that such information does not directly give the pore-size distribution is obvious. However, pore-size distribution obtained from Nitrogen adsorption agrees well with that calculated from mercury porosimeter data on the assumption of parallel tube model.[26] Mercury porosimetry will not detect the dimensions of those pores that are accessible only through necks narrower than the pore itself. The volume of these pores of limited accessibility will be erroneously assigned the dimensions of the largest neck leading to these pores. They analyzed a number of natural substances and concluded that the pore size distribution can be represented by three parameter modified Maxwellian distribution function. Haring's two parameter distribution function is simpler and should be preferred.

Meyer[2] attempted to correct this distortion in the pore-size distribution due to the presence of the pores of limited accessibility. On the assumption that the pore sizes follow Poisson distribution, he calculated the probability of a pore of radius r_o not being connected to the pores of radius $r \geq r_o$. This probability was used to correct the mercury porosimeter values for the 'Ink-bottle' effect. The details of the derivation and the computational method is given in Appendix B.

Dullien[27] proposed to determine 'two dimensional' pore-size distribution by injecting Wood's metal into the sample and using micrographic analysis. Apart from the experimental scheme, he has not published his results yet.

2.3 Characterization of Porous Media on the Basis of Capillary Pressure Curve:

The earliest attempt in this direction was made by Leverett[28,29] who put forward a semi-empirical relation

$$J(S_w) = \frac{P_c}{\gamma \cos\theta} \left(\frac{K}{f}\right)^{\frac{1}{2}} \qquad (2.6)$$

where $J(S_w)$ = capillary pressure function and is dimensionless function of wetting phase saturation

on the basis of dimensional analysis. Leverett's data showed that a plot of $J(S_w)$ vs S_w (wetting phase saturation) yielded a unique curve which described the capillary retention of wetting liquid in clean, unconsolidated sand.

Rose and Bruce[30] extended Kozeny-Carman treatment to relate capillary pressure with porosity, permeability and textural constant known as Kozeny constant. The expression suggested is:

$$\frac{P_T}{\gamma \cos\theta}\left(\frac{K}{f}\right)^{\frac{1}{2}} = \left(\frac{1}{k}\right)^{\frac{1}{2}} \qquad (2.7)$$

where P_T = threshold pressure i.e. $\lim_{Sw \to 1} P_c = P_T$

But these expressions, apart from classifying the porous media and in some cases predicting flow behaviour, did not give any insight in the distribution of the pore-sizes. Recently Haring and Greenkorn[23] have derived an expression for wetting phase saturation from P_c curve as

$$S_w = \frac{\int_0^{\frac{1}{P_c^*}} \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)}{\int_0^{1} \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)} \qquad (2.8)$$

where $P_c^* = \frac{P_c}{P_T}$

P_T = threshold capillary pressure

α & β = parameters of pore size distribution.

Thus in case we are able to estimate α and β from P_c vs S_w curve, we really have an expression for pore-size distribution F(x),

$$F(x^*) = \frac{\int_0^{x^*} x^{\alpha} (1-x)^{\beta} \, dx}{\int_0^1 x^{\alpha} (1-x)^{\beta} \, dx} \qquad (2.9)$$

where $x^* = r/r_{max}$, the ratio of pore-size to the largest pore size.

This $F(x)$ is then used to calculate the wetting fluid saturation, S_w, for any P_c by the Eq. (2.8).

2.4 Plan of Attack:

From the analysis of the past work, it is obvious that the relation between the pore-structure, its distribution and the capillary characteristics of porous media is not well understood. Meyer[2] assumed Poisson distribution and suggested a method for applying correction for 'ink-bottle' effect. Haring and Greenkorn[23] suggested a statistical model for capillary pressure which could be useful in mass transfer calculations. But they approximated the pores by straight cylindrical tubes beside assuming unimodal distribution of the pores. In real porous media these are not strictly valid assumptions. In the interpretation of P_c curve for pore-size distribution, Fatt[1] used an arbitrary factor (α) which could take the value -1. There seems to be considerable disagreement between different workers regarding the value of this factor, α. Meyer[2] had implicitly assumed the value 1 for α in his calculation of

of probability function for the pores of limited accessibility.

To find a method which can interpret P_c curves satisfactorily, we will do the following:

a) Networks will be constructed for different pore-size distributions and by allowing them to imbibe nonwetting fluid under successively higher pressure, P_c curves will be generated for different distributions.

b) An attempt will be made to workout a procedure for interpreting P_c in terms of the pore-size distribution. To arrive at the number distribution of the pore-sizes from P_c curve, Fatt's[1] model with different values of α will be tried and the result willbe compared with the actual input to the network.

c) Existence of 'ink-bottle' effect in a real porous system will be studied by the method proposed by Meyer[2]. The corrected pore-size distribution (volumetric) will be matched with the one estimated from the P_c curve to determine whether the effect is significant in natural system. Corrected pore-size distribution from the network P_c curve will be compared with the actual distribution to test the reliability of the approach. To this end, different expressions for characteristic volume, in Meyer's method, in terms of power to pore radius, will be tried and compared with the actual input to the network.

d) To obtain the pore-size distribution from an actual P_c curve, Haring and Greenkorn[23] model will be used to estimate

the parameters of distribution by non-linear least square method. Network model will be used to determine how close the estimated distribution is to the actual distribution.

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CHAPTER 3

MODELS USED IN THE PRESENT WORK

3.1 Generation of P_c Curve from Known Pore-Size Distribution:

Use of network model for generation of P_c curve consists of two steps:

a) Construction of a network simulating the porous material with a known pore-size distribution. This idea was originally suggested by Fatt[1] and the methodology followed here was developed by Singhal[22]. In the network, pores could merge at and branchout from a node point. A network of the size 6 x 8 was used in our simulation in which the nodes were arranged in square grid pattern. Thus at each node point a maximum of eight tubes could meet. Fatt[31] suggested, from experimental observations that each tube was connected to 10 other tubes implying that on the average 6 tubes could meet at a point. This fact was incorporated in the model by modifying the cumulative pore-size distribution obtained from capillary pressure curves, so that 25% of the tubes have zero radius. This was achieved by compressing the real distribution between 0.25 to 1.0 instead of 0.0 to 1.0 by the following expression:

$$l' = 0.75l + 0.25$$

where l' = new value of the distribution

l = original value

Whereas the tube radius and location were assigned in random manner by Monte-Carlo technique, the tube length could assume only two values viz. equal to the side length of the square or its diagonal length. The grid length was arbitrarily chosen. The list of the input to a typical network simulation program is given in the Table 1. The details of simulation has been discussed by Singhal[22] and for the sake of completion, the relevant points are included in the Appendix A.

b) Generation of Capillary Pressure Curve: Capillary pressure characteristics of the network is evaluated by modifying and adapting the computer program written by Singhal[22]. Some additional checks have been introduced in the program to verify that material balance for each fluid as well as for the total fluid is satisfied at each stage of computational cycle.

Initially the network is assumed to be full of wetting fluid and is allowed to be displaced by non-wetting fluid. A fixed pressure drop (ΔP) is applied across the network and it is allowed to desaturate the wetting fluid in a quasi-static manner. This process continues till outflow from the network in a particular time step is negligibly small; implying equilibrium fluid distribution in the model. Theoretically in a quasi-static process the time step should be as small as possible. But this would mean larger computation time. Hence we used the time steps of the order of 200 μsec. initially and later increased it as the desaturation process proceeded.

Instead of waiting indefinitely for zero outflow to occur in a time interval, we cut short the calculation for a ΔP whenever the outflow in a time step is less than or equal to 1% of the outflow in the first time step. The saturation of the wetting phase in the model is then calculated thus obtaining one point on the P_c vs S_w curve. Pressure drop (ΔP) across the model is then successively increased and in each case the equilibrium wetting phase saturation is obtained. In this way the whole P_c vs S_w curve can be obtained over any range of pressure and saturation.

Singhal[22] used a trapping factor $(0.2/\sqrt{\mu_o \mu_w})$, where μ_o and μ_w are the viscosities of non-wetting and wetting fluid respectively, to trap the fluids in the pores during desaturation. This was merely a correction factor to match the model behaviour with actual samples. In static process like capillary desaturation, the viscosity of the fluid is not of any significance as far as equilibrium saturation is concerned. Equilibrium saturation of the wetting fluid depends solely on the curvature of the remaining fluid interfaces in various tubes. In our simulation of the network the tubes have assumed the size equivalent to the volumetric average radius of the pores. In real porous systems (granular) the pores are convergent-divergent in shape. As a result the neck radius in any tube is definitely smaller than the volumetric average radius. As the capillary pressure of any tube is determined

by the size of the narrowest constriction in the tube, the actual capillary pressure will always be larger than that calculated from the average radius.

In the present work, the trapping factor is the ratio of the volumetric average pore radius to the neck radius for each tube, thus implicitly simulating the convergent - divergent shape of the pore channels. At every stage the pore-entry capillary pressure is modified by this factor to calculate P_T at the neck. This pressure is then used to determine whether the interface will move through the pore or will be blocked.

3.2 Correction for "Ink-Bottle" Effect:

In natural porous systems pores are surrounded by smaller pores; recognized as "ink-bottle" effect by Meyer[2]. This results in assigning larger volume to the smaller pores while the volumetric share of larger pores is less than the actual volume. Evidently the use of bundle of tubes model to calculate pore size distribution is likely to be erroneous. Meyer[2] attempted to correct the measured data for this effect by calculating the probability of a larger pore not being connected through equal or larger pores to the mercury source in mercury porosimetry. He assumed that pore-sizes are randomly distributed and follow Poisson's distribution. In deriving the probability $\int_0 (r_o, r)\, dr$, he overlooks the fact that the pores are mutually exclusive and asserts that this will not introduce any serious error in calculation since only

the 'zero' term in Poisson's distribution is used for calculation. Also, assumed randomness of pore sizes exclude from consideration clusters of very large or very small pores such as fractured or vuggy system.

Other simplifying assumptions made by Meyer are: (i) that the centre of an r pore lying in volume $v(r_o, r)$ will ensure its being connected to an r_o pore, (ii) that only those pores which are isolated from all equal or larger pores will fail to fill and (iii) volume of a pore may be expressed as Kr^3 where K is a constant.

The first assumption is valid for spherical pores and seems intuitively sound for others. The implication of the second assumption is that isolated groups of mutually connected pores are not being considered. This, of course, is a serious simplification but necessary for handling the difficult subject of aggregates in a random distribution. It is hoped that the correction applied for individual isolated pores is the major correction needed. The third assumptions implies that larger pores have larger length associated with them. This sounds reasonable as the larger pores are associated with larger grains for uniform packing. This assumption has one snag that K is not a constant. However, K as a constant appears only under the integral sign and cancels out. The assumption, in fact, is not that K is a constant but that its mean value in one integral is equal to that in the other.

Hence, he proposed that measured pore-size distribution should be corrected by this method to obtain actual distribution for granular porous system. Details of the method is given in Appendix B.

Computer program, written for this scheme, is given in Appendix D.

3.3 Haring and Greenkorn Model:

Haring and Greenkorn[23] have suggested the use of two parameter incomplete Beta function as the universal distribution function for the pore-size in a porous body. It was claimed by them, and rightly so, that almost any unimodal distribution, whether symmetric or skew, could be approximated very closely by the adjustment of the two parameters. Normal distribution of the pore-size was not favoured for the following two reasons:

i) the distribution is symmetrical.

ii) the independent variable varies from $-\infty$ to $+\infty$;

none of which is strictly true for a porous media.

One more implicit assumption in their approximation is that the ratio of minimum to maximum pore size is zero, which is not always true. That seems to be the reason, why for a granular pack the average pore size computed on the basis of this distribution function comes to even less than the minimum pore-size computed from geometrical considerations of granular packing. Also, the average pore length is calculated to be equal to half the average particle diameter; while ideally

it should be equal. This fact has been pointed out by Paytakes, Tien and Turian[24]. However, this inconsistency may be over come by slightly modifying the distribution function to:

$$g(r^*) = \frac{\int_0^{r^*} (x-x_m)^{\alpha} (1-x)^{\beta} \, dx}{\int_0^1 (x-x_m)^{\alpha} (1-x)^{\beta} \, dx} \qquad (3.1)$$

where r^* = dimensionless radius of the pore. The ratio of pore radius to the largest pore radius.

x_m = The ratio of smallest to the largest pore radii

α, β = Parameters of distribution.

Based on the assumption that the actual pore-size distribution can be approximated reasonably by incomplete Beta function, Haring[23] et al arrived at the following expressions for the wetting fluid saturation, S_w:

$$S_w = \int_0^{\frac{1}{P_c^*}} \frac{(\alpha+\beta+3)!}{(\alpha+2)!\,\beta!} \, x^{\alpha+2} (1-x)^{\beta} \, dx \qquad (3.2)$$

$$= B\left(\frac{1}{P_c^*} ; \alpha+2, \beta\right) \qquad (3.3)$$

where $B(\frac{1}{P_c^*} ; \alpha+2, \beta)$ is incomplete Beta function with $\alpha+2$ and β as parameters.

P_c^* Dimensionless capillary pressure, P_c/P_T

P_T Threshold capillary pressure i.e. P_c when $S_w \rightarrow 1$.

In this work we shall try to fit the Eq.(3.3) by non-linear least square method. Standard IBM program SDA-3094 will be used for this purpose.

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CHAPTER 4

RESULTS AND DISCUSSION

As already mentioned in earlier chapters network seems to be a good model for predicting the flow behaviour of porous media. A part from its closer and better physical similarity with porous media, capillary pressure curves obtained from it look quite realistic. However, there may be some weaknesses in this model which will be discussed later in this chapter.

Capillary pressure (P_c) vs wetting fluid saturation (S_w) from the networks are given in Figs. 2a to 2f. Each network was generated from a specified pore-size distribution, which was assumed to represent a hypothetical porous medium. Pore-size distribution used to generate networks were; arbitrary distribution, Beta distribution and Poisson distribution. Besides, a couple of bimodal arbitrary distributions were also used. The networks with bimodal distribution were used to find out if the P_c curve could give some indication of the multi-modality in the distribution. In each case, except the first network, the largest pore-size used was 20 μ. The input distribution was compressed in each case between 0.25 to 1.0 to accommodate Fatt's Beta factor as suggested by Singhal[22].

Inspite of the very distinct and extreme forms of the distributions used to generate the networks, the calculated

P_c curves were not significantly different from each other. Thus giving the impression that capillary pressure is not a very strong function of the pore-size distribution in the network. Also threshold pressures (P_T) obtained from the network P_c curves (corresponding to $S_w = 1.0$) do not always agree with that predicted from the bundle of tubes model. Threshold pressure, from the definition, depends on the size of the largest tube in the input face of the network. But, in view of the fact that tubes are assigned randomly at different node points, it is possible that the largest size tube may not occur at the input face. In that case P_T predicted from the bundle of tubes model will be different from that evaluated from the network. From the inspection of Fig. 1.e, it is obvious that the largest tube size (20 μ) does not appear in the input face and hence the calculated P_T from the network is higher than that predicted for 20 μ tube radius (0.259 psi). Also, during the computation of P_c curve from networks, more than one fluid/fluid interfaces were observed in a continuous flow channel. This factor has not been accounted for in the bundle of tubes model and can be one of the reasons resulting in the difference in the two values of P_T.

Other features of the network likely to have influenced the P_c curves are; (i) number of tubes (ii) ratio of the tube length to the radius (iii) the extent of inter-connection between the tubesand (iv) existence of different flow regimes

in flow channels.

(i) Fatt[31] estimated number of pores in a 1/2" cube sample of sandstone to be of the order of 10,000. In our networks, the number of tubes varied between 89 to 101. Whether such a small number of tubes (pores) could reasonably approximate the flow behaviour of real porous media with huge number of pores, is open to doubt. With such a small number of tubes, it is the relative position of the tubes which matters more than the size distribution. If the investigation could be repeated with larger sizes of networks (500 to 1000 tubes), the result may throw some light over this question. Our limitation in computer memory and time prevented us from trying bigger networks. Fatt[1] asserts that tubes more than 200 in number do not substantially affect the nature of P_c curves from networks. However, he did not compare any experimental P_c curve with that of a network to prove his point that tube number is not a critical factor.

(ii) The second factor, which seems significant, is the ratio of the pore length to the pore radius. In our networks, this ratio varies from about 6 to 60 depending on the size and the location of the tubes relative to the grid. Earlier investigators suggest that the length of a pore varies according to some power of r. This factor varies between 0 and 1, according to Dallavalle[3]. Fatt[1] puts this value at -1. In one of our calculations grid size was reduced to about 1/5th

of the original value thus reducing the maximum value of length to the radius ratio from 60 to 12. The two P_c curves (Fig.1h) are not significantly different. Further investigation with different values of the grid-size is desirable before drawing any conclusion.

(iii) The third factor to be considered is the Beta factor suggested by Fatt[1] and used by Singhal[22] in his simulation of networks. This factor essentially represents the extent of interconnection between the pores in porous media. Applied to networks, this implies average number of tubes meeting at a node point. Fatt[32], from his experimental observations, points out that in a sandstone rock each pore is connected to 10 other pores thereby implying that on the average 6 tubes should meet at a node point. In Fig. 2h the three P_c curves have been obtained with different values of the Beta factor. It is obvious that the two P_c curves, for Beta factors 6 & 8, are not very different from each other, the P_c curve for Beta factor equal to 4 is significantly different from the other two. Hence it may be inferred that the extent of interconnection in a network, represented by Beta factor, is quite important and is likely to be different for different media. In our simulation this factor has been taken equal to 6.

(iv) There is experimental evidence to support the existence of different flow regimes in flow paths of physical models of porous media where one fluid displaces the other. In such systems, the interplay of viscous and capillary forces comes into existence and the flow regimes depend on ΔP and flow

rate. This phenomenon is accounted for in the network but not in the bundle of tubes model. This could be another weakness of the bundle of tubes model. However, for mercury-vacuum system this situation, of different flow regimes in flow paths, is not likely to occur.

Simulated networks used for generation of P_c curves were tested for goodness of fit by χ^2 test. The pore-size distributions of the simulated networks were not found to be similar to the input distributions within a reasonable confidence limit. We suspect that the scheme of pseudo random numbers used in the simulation might not have been truly random. Consequently it was decided to use the actual distributions of the networks rather than the input distributions which they were supposed to represent. Any further work in this direction should ensure that the simulated network does pass χ^2 test to represent the input distribution. However, the weaknesses mentioned above may not be very serious in view of the results obtained from the network model.

Since our networks have discrete pore-sizes, ideally some step type P_c curves would have been expected. But from the limited number of the points on the P_c vs S_w plot, a smooth curve could be drawn. It appears that the pore-sizes may not be the exclusive factor determining the value of capillary pressure in a porous medium. Other factors like connectivity etc might also be important.

The idea of relating P_c to the size of the pores has its root in the bundle of tubes model of porous media. Even the model proposed by Haring and Greenkorn[23] are the modification of the same model, providing random orientation of the tu tubes and consequent inter-connections. Therefore to correct for inter-connection between the pores, some modification is called for in the interpretation of P_c curves based on this model.

The effect of "ink-bottle" phenomena seems to be significant in the networks, resulting in the cumulative pore-size distribution (volumetric) obtained from P_c curves, being quite different form the actual distributions. Actual distributions were computed by counting the number of tubes of different size and calculating their volumes. The difference in the two distributions can be clearly seen in the Fig.3a to 3f. Attempts were made to correct the distributions (obtained from P_c curves) by Meyer's method[2] for "ink-bottle" effect. In using this method, slight modification was made in the scheme given in the Appendix B. As is obvious, in a network, tube lengths are independent of radius. As a result the pore volume as well as the characteristic volume defined in Meyer's method becomes proportional to the radius squared rather than radius cubed. The corrected distributions (volumetric) is compared with the actual and that obtained from P_c curves in Figs. 3a to 3f.

Effect of the pores of limited accessibility ("ink-bottle" effect) on the volumetric distribution appears quite-pronounced in some of the natural substances investigated by us. The substances included porous plate, fritted glass, pelleted gel etc. Meyer's method as given in the Appendix B was used for these calculations and the result is given in Fig. 4a to 4d. P_c data for these substances were obtained from Ritter and Drake[25] and are reproduced in the Table 3. The same method was applied to P_c data of some sandstone samples obtained from literature but no appreciable difference in the experimental and corrected distributions was observed; implying that this phenomenon is not very significant in those samples. In an attempt to closely approximate the actual pore-size distribution, the exponent of r in Meyer's method was given a number of values (3 to 1.5). The curves with the exponent equal to 1.5 were observed to be better than others in approximating the actual curves (Figs. 5a to 5f). Physically this means that the pore length is $\propto r^{-0.5}$. This distortion from the expected relation of $l \propto r^{0}$ may be due to a number of factors, like some bias in our networks, and to a greater degree on the extent of inter connection between the pores.

Attempts were also made to estimate number pore-size distribution from P_c vs S_w curves obtained from the networks. In the absence of an analytical expression incorporating network concept of porous media, investigations were carried out

to find out if Fatt's model, of bundle of tubes, could be useful. In that model (Eq. 1.3) Fatt[1] used an exponent α which related the pore length to the radius. The same equation, with the different values of α, was used to calculate pore-size distributions (number) from P_c curves of the networks. It is apparent from Figs. 5a to 5f that for the values of α lying between -2.5 to -3.5 (mostly -3.0) the calculated distributions are reasonably close to the actual distribution. The physical implication of this value is that the pore length (l) $\propto r^{-3.0}$. In our networks the tube lengths were independent of the radius. But because of the fact that we have distinctly two groups of lengths, side lengths and diagonals of the grid, in our networks, pore lengths could not be said entirely independent of the radius. Also, the small sample size, extent of interconnections and the non-randomness of the pseudo random numbers used in simulation, might have introduced some fictitious relation between l and r.

Haring and Greenkorn[23] model relating pore-size distribution (number) to capillary pressure and saturation, was tested by estimating the parameters of the distribution from P_c vs S_w curves by non-linear least square technique. These parameters were put back in incomplete Beta distribution function to calculate the number distribution. These calculated pore-size distributions did not match the actual distribution obtained by counting the number of the tubes from the networks.

One of the curves fitted to the network P_c curve is given in Fig. 6.

From the limited number of analysis performed by us, it is doubtful whether this model could at all relate the pore-size distributions to P_c curves of real porous media.

From our study it can be said that networks could be used as a valid model of porous media and pore-size distributions could be obtained from P_c vs S_w curves.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

The classical model (bundle of tubes) of porous media have a number of weaknesses. As a result the interpretation of P_c curve based on this model is likely to be erroneous. Network is a better physical model of the porous media and P_c curves obtained from it is quite realistic. True pore-size distributions (volumetric and number) can be better estimated from P_c curves by modified Meyer's and modified Fatt's method indicated in this work.

Future work in this direction should ensure that the actual pore size distribution (number) of the simulated networks reasonably match the input distribution. More work is needed to find out the effect of tube length-radius ratio, the extent of interconnection, and number of tubes in the network on the P_c curve generated. Experimental work with physical networks are necessary to verify these theoretical findings.

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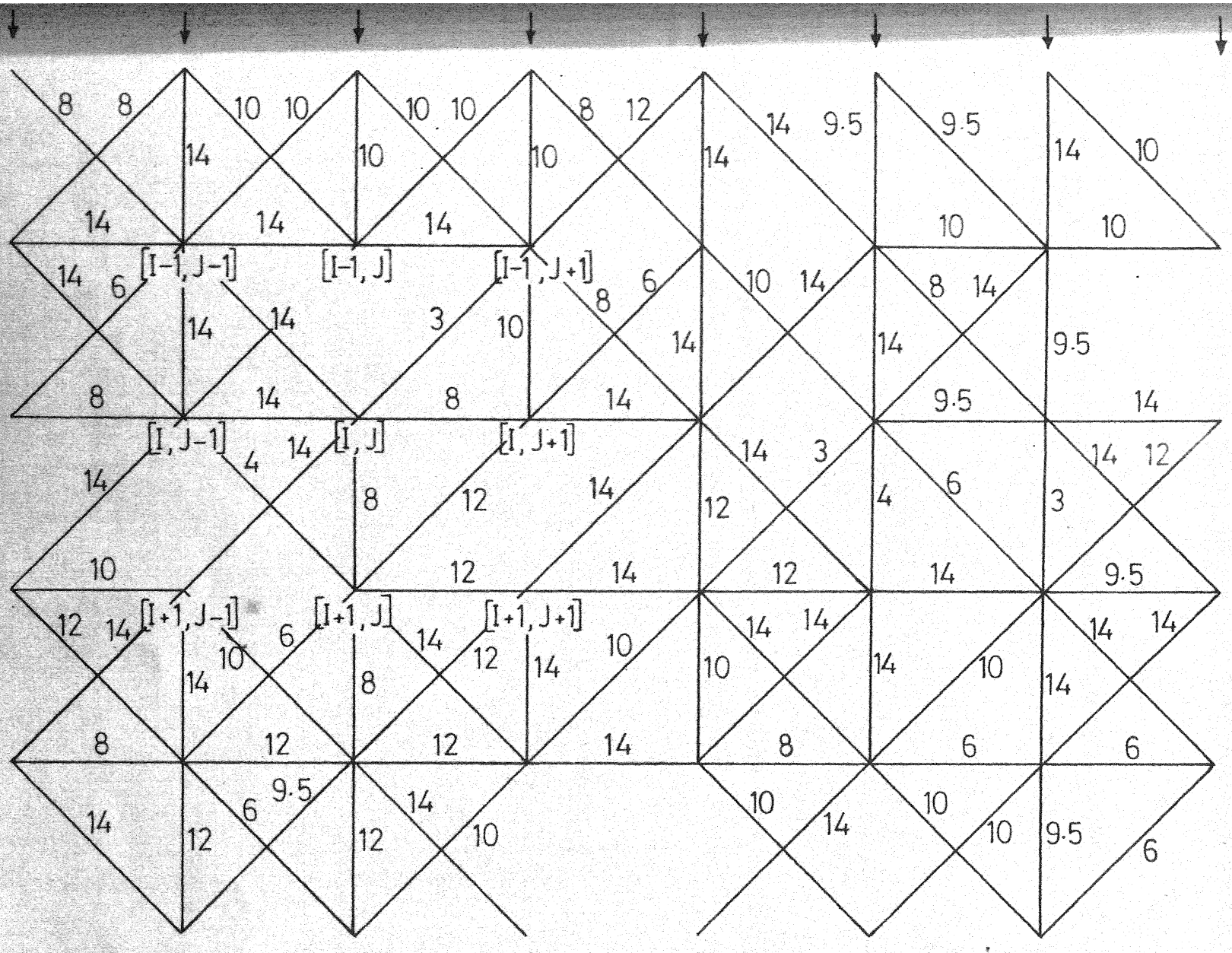


Fig. 1a - A typical network used for generation of capillary pressure curves. Input data table 1 . Numbers indicate tube rad. in microns.

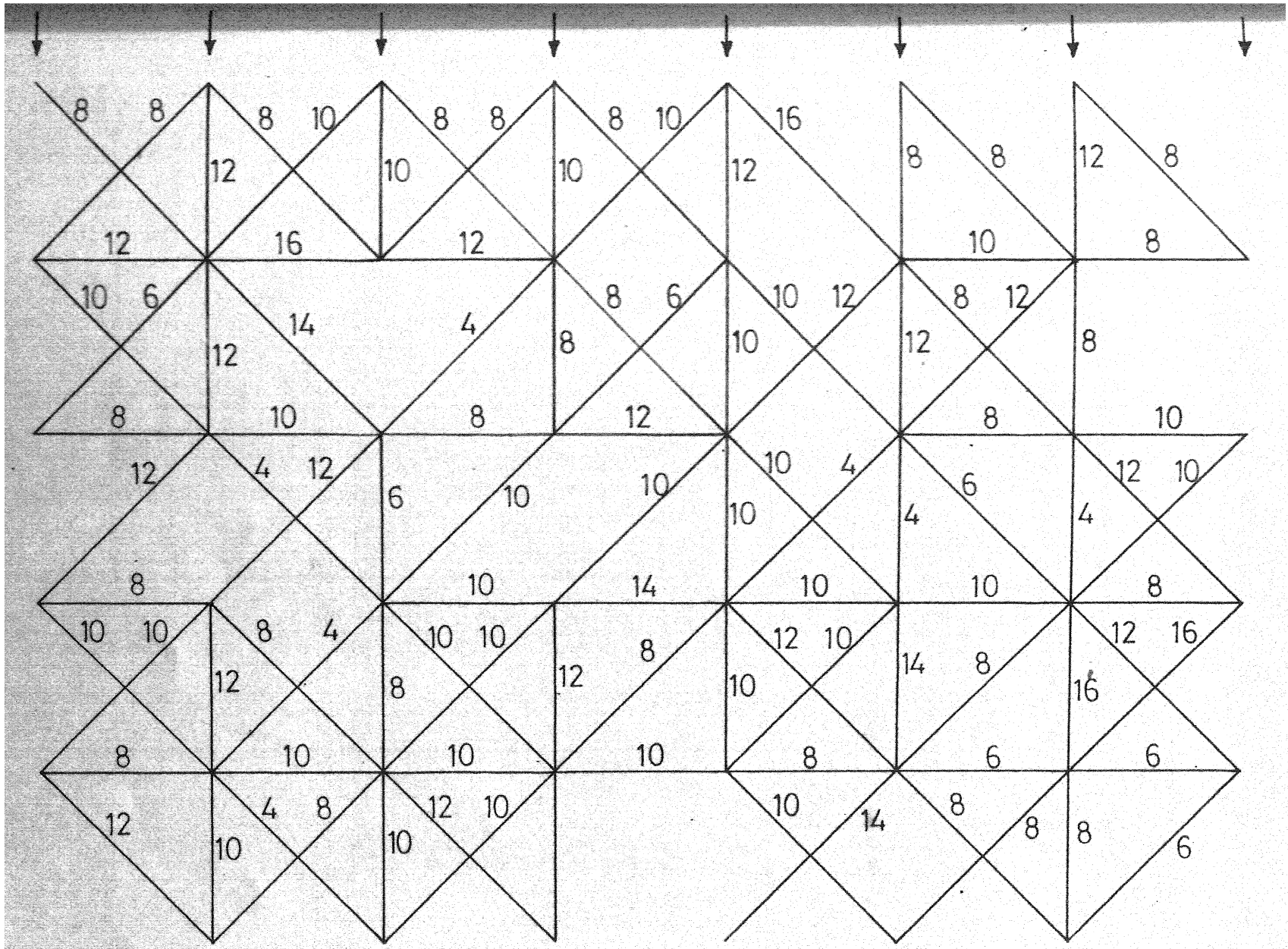


Fig. 1 b- Network for incomplete beta distribution.
(Parameter 3·5, 5·5)

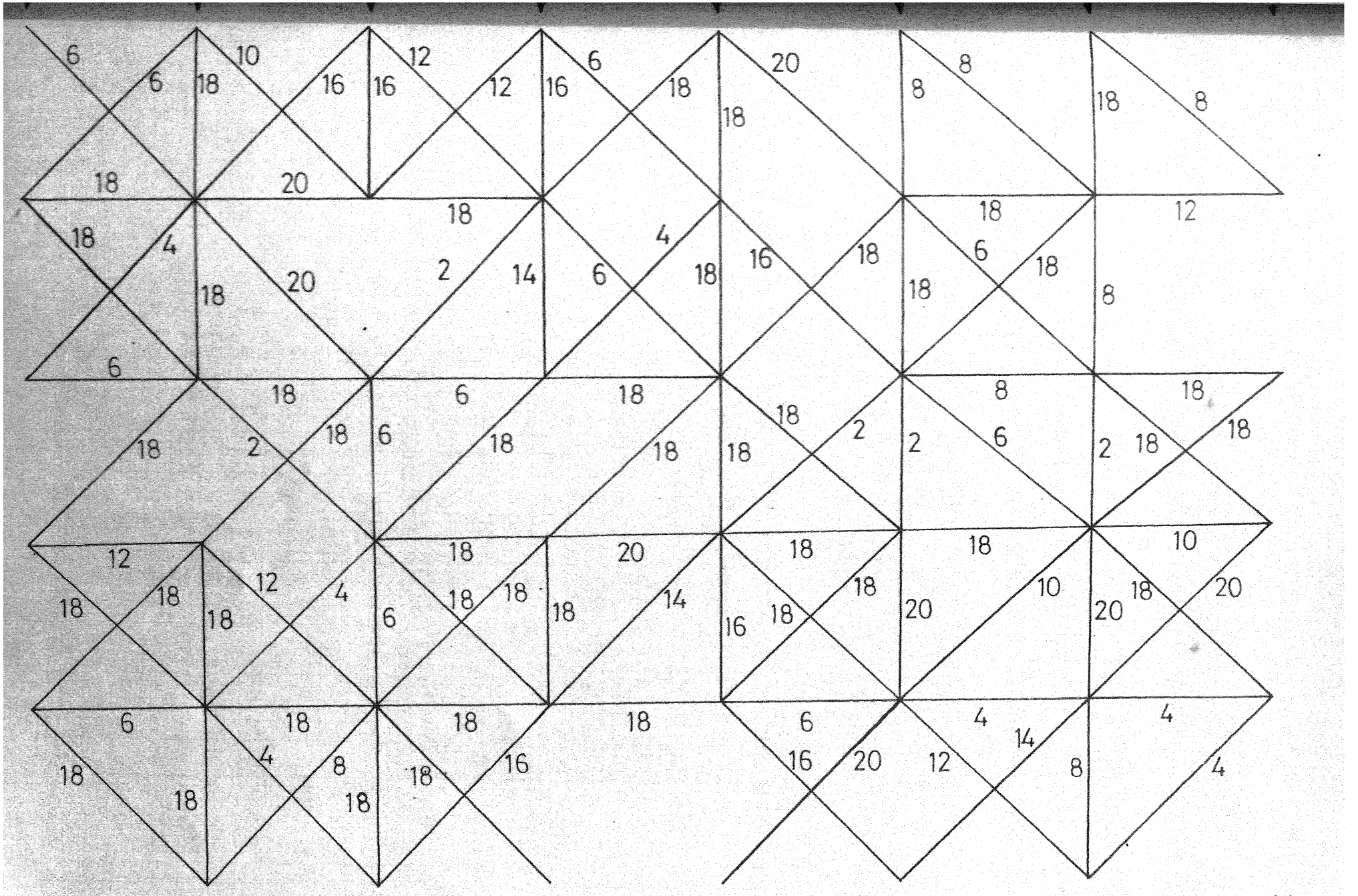


Fig. 1c - Network from arbitrary bimodal distribution. Table 2.

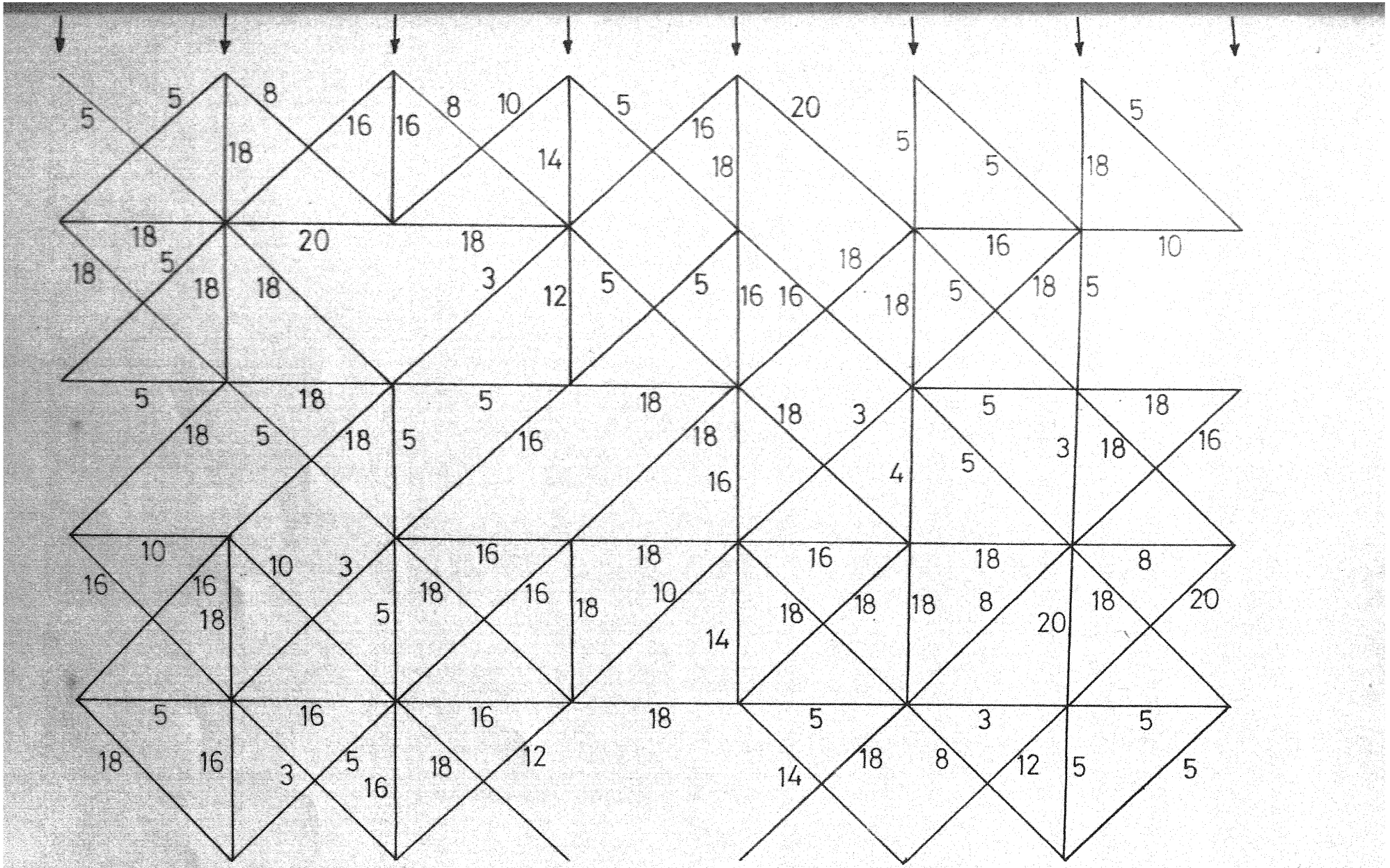


Fig 1 d - Network from arbitrary bimodal distribution. Table 2.

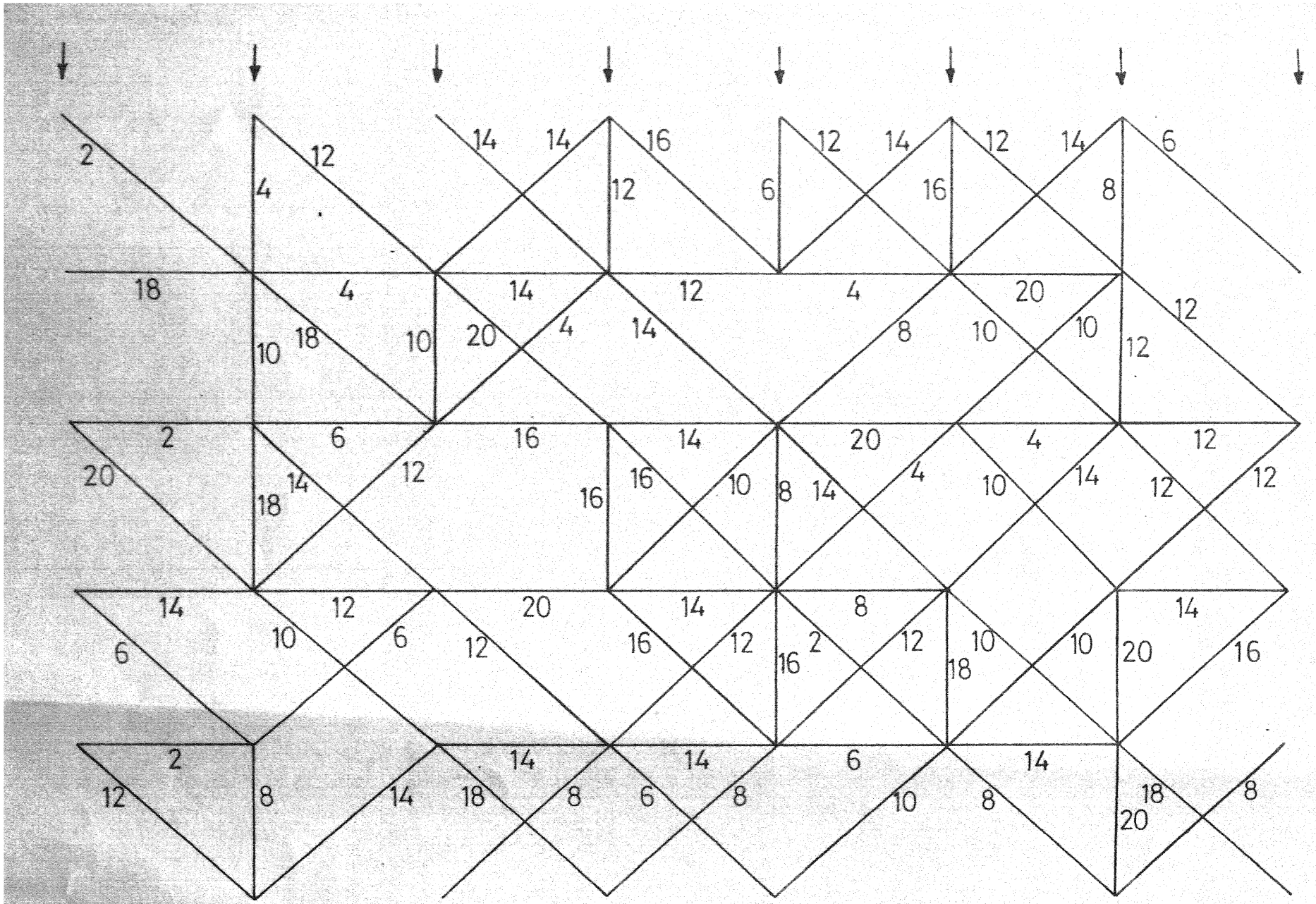


Fig. 1e - Network used to obtain P_c vs. S_w curve (Fig. 2e) indicating absense of the largest size tubes in the input end. Input incomplete beta distribution with parameters 1·0, 1·0 : Numbers indicate tube radius in micron.

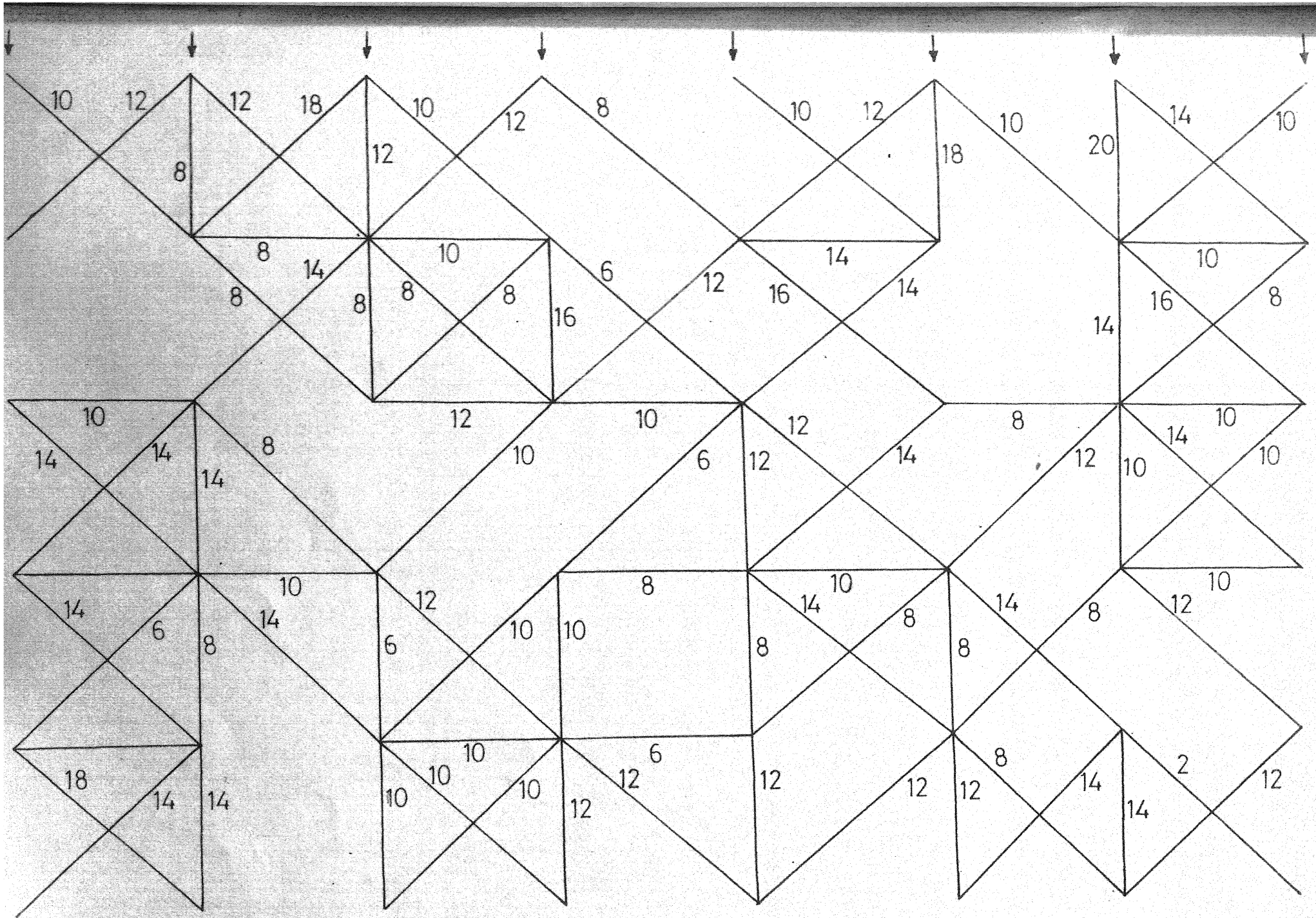


Fig. 1 f - Network for poisson distribution ($\lambda = 10$).

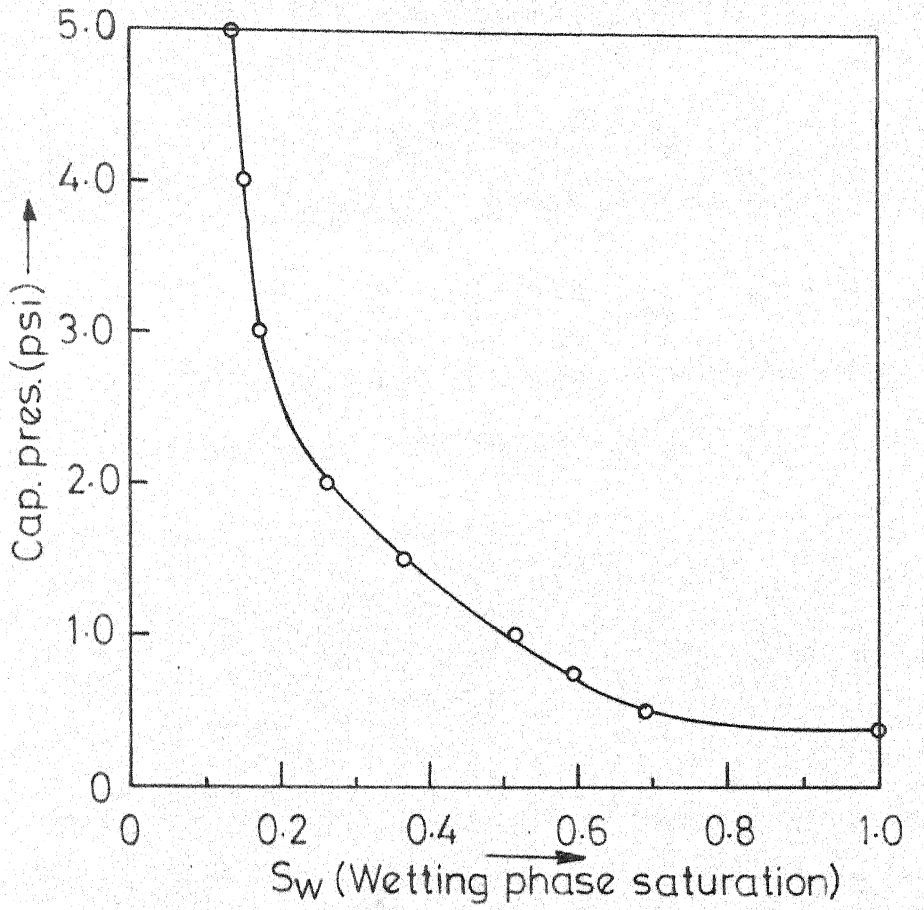


Fig.2a-P_c vs. S_w curve obtained from network I Fig.1a.

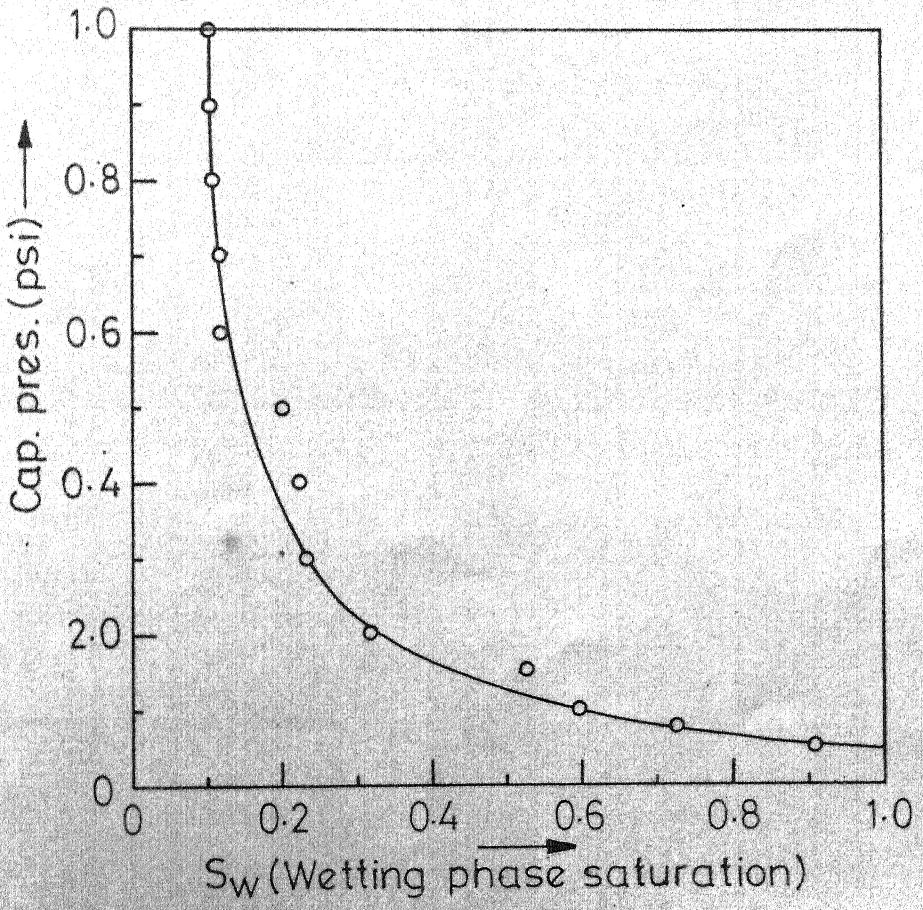


Fig.2b-P_c vs. S_w curve obtained from network II Fig.1b.

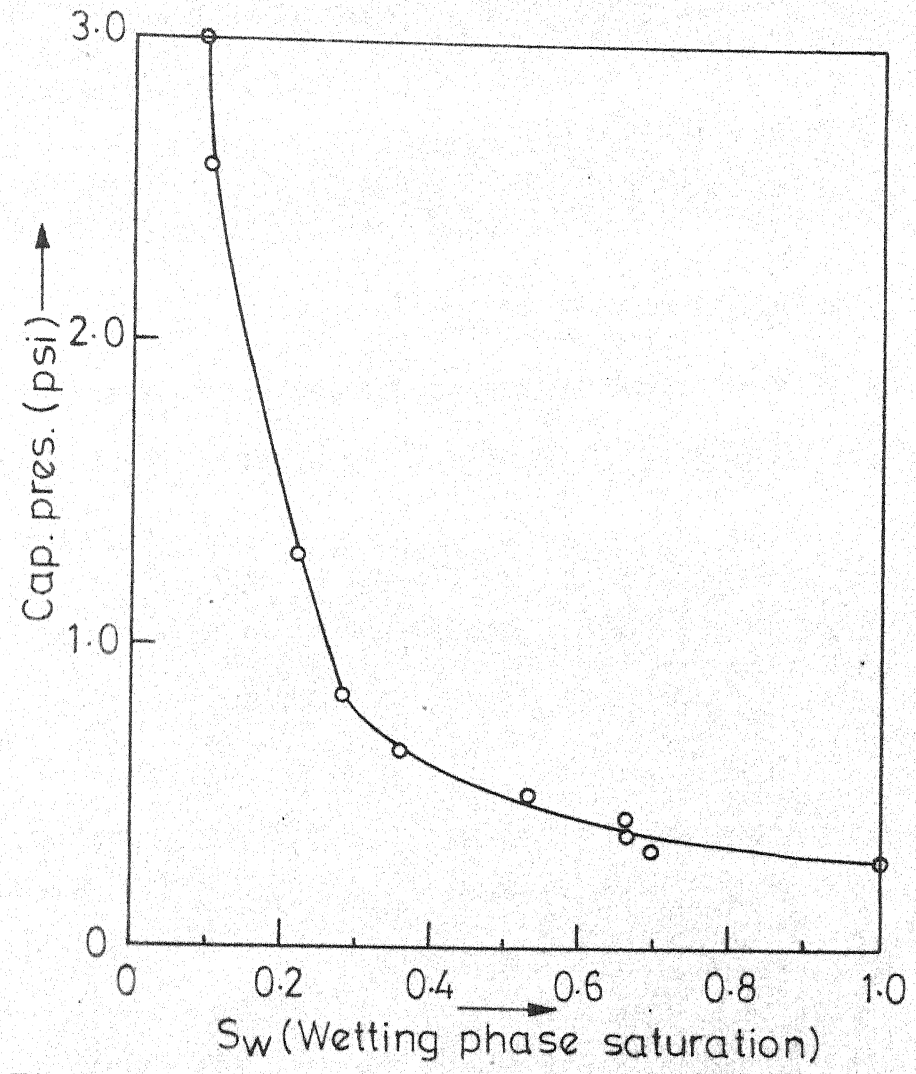


Fig.2c - P_c vs S_w curve for network III Fig.1c.

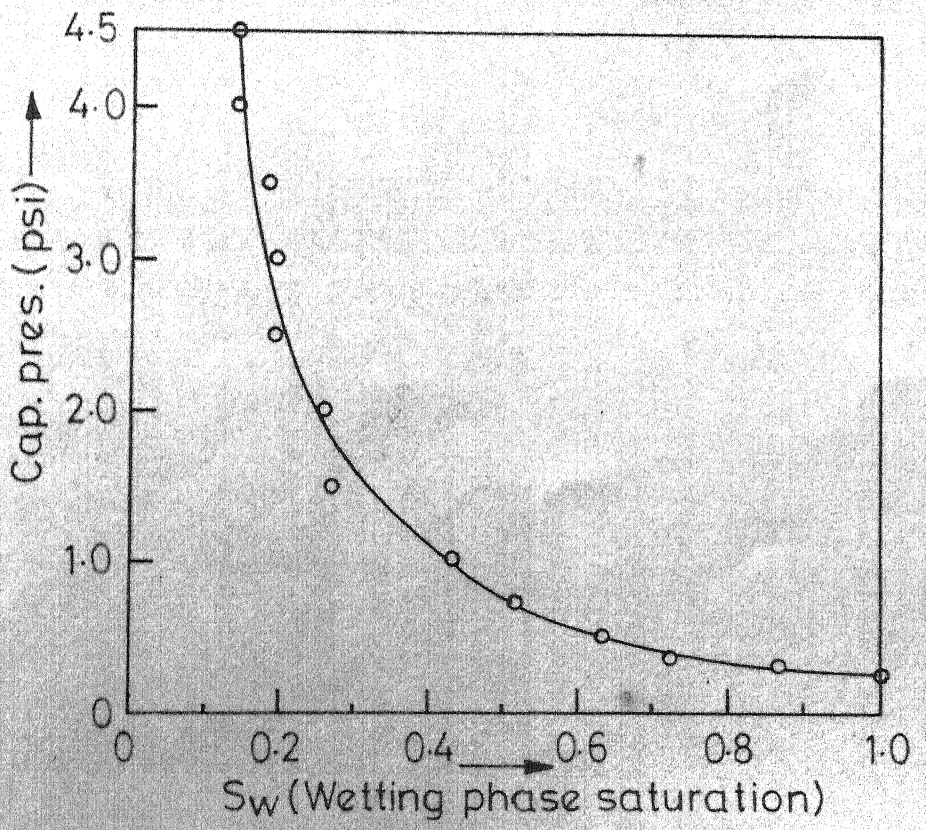


Fig.2d - P_c vs. S_w curve for network IV Fig.1d.

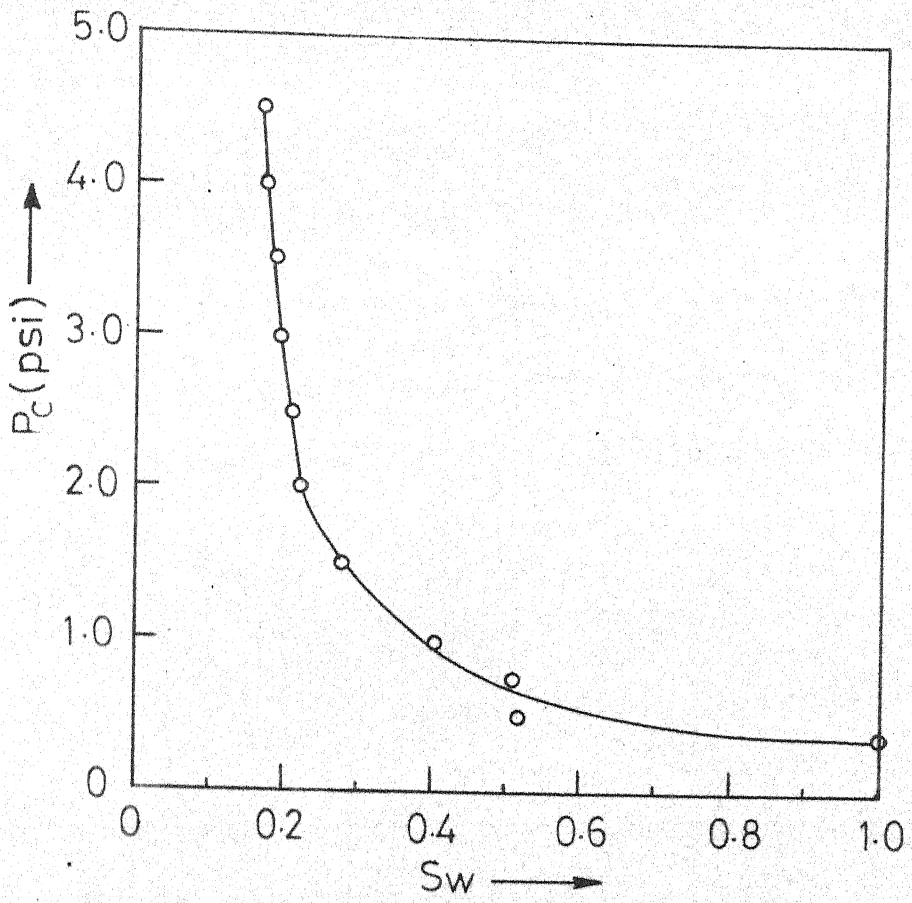


Fig. 2e - P_c vs. S_w curve for network V Fig. 1e.

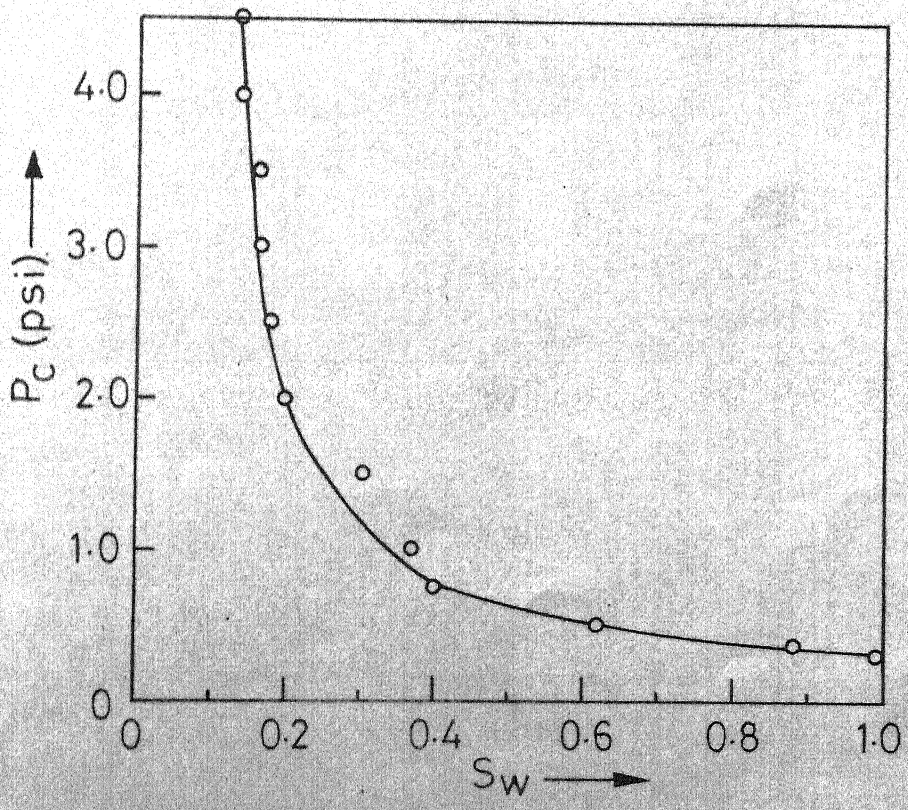


Fig. 2 f - P_c vs. S_w curve for network VI Fig. 1 f.

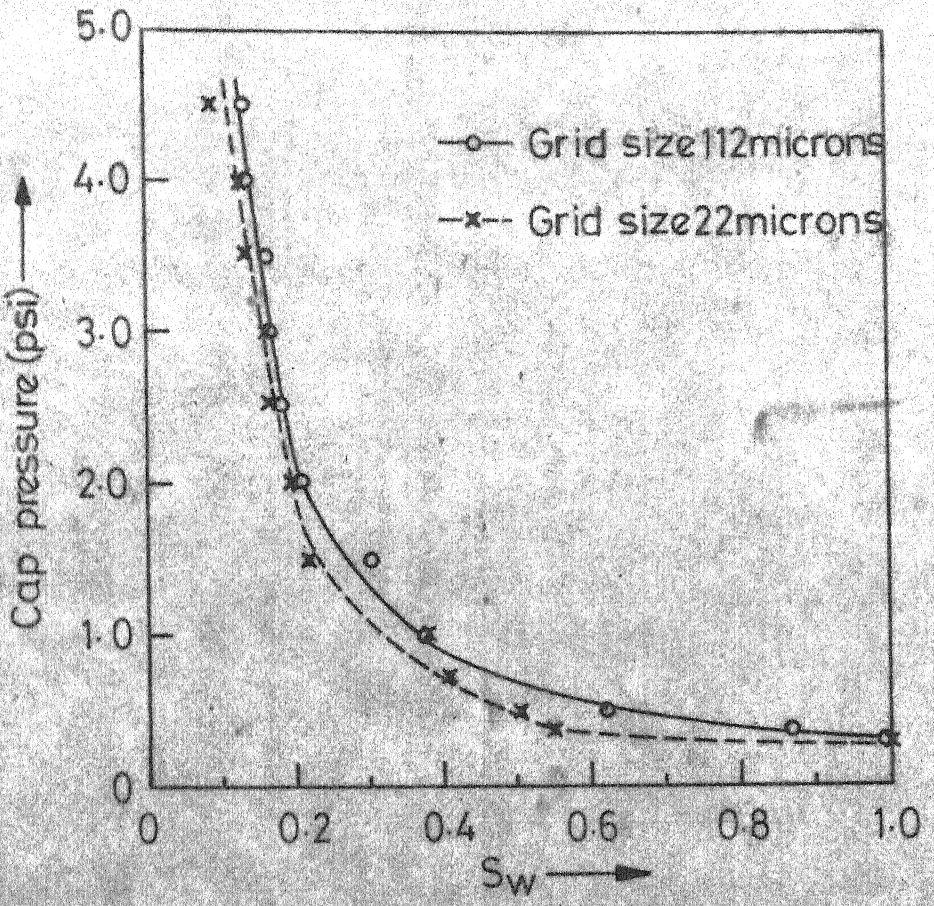


Fig.2g-Effect of grid size on P_c curve. Network VI.

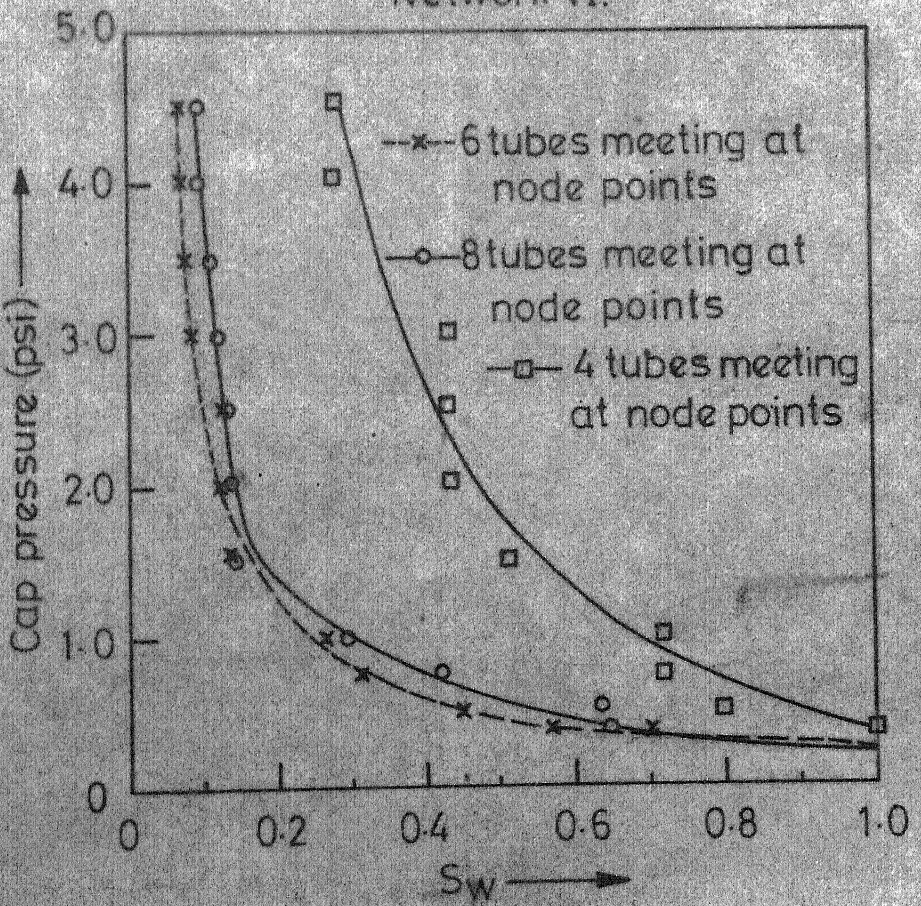


Fig.2h-Effect of network inter connections of P_c curve. Network VI.

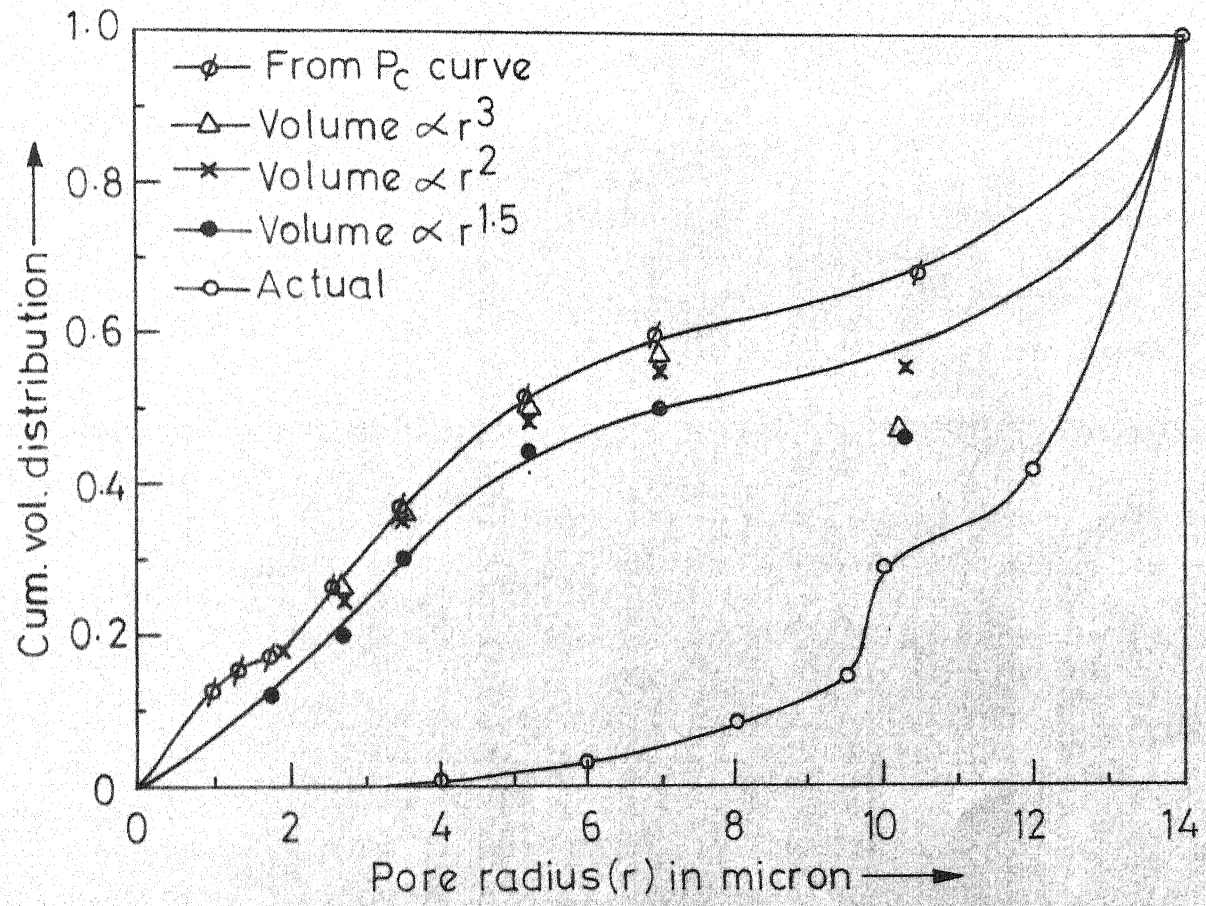


Fig. 3a - Correction in volumetric distribution by Meyer's method. Network I.

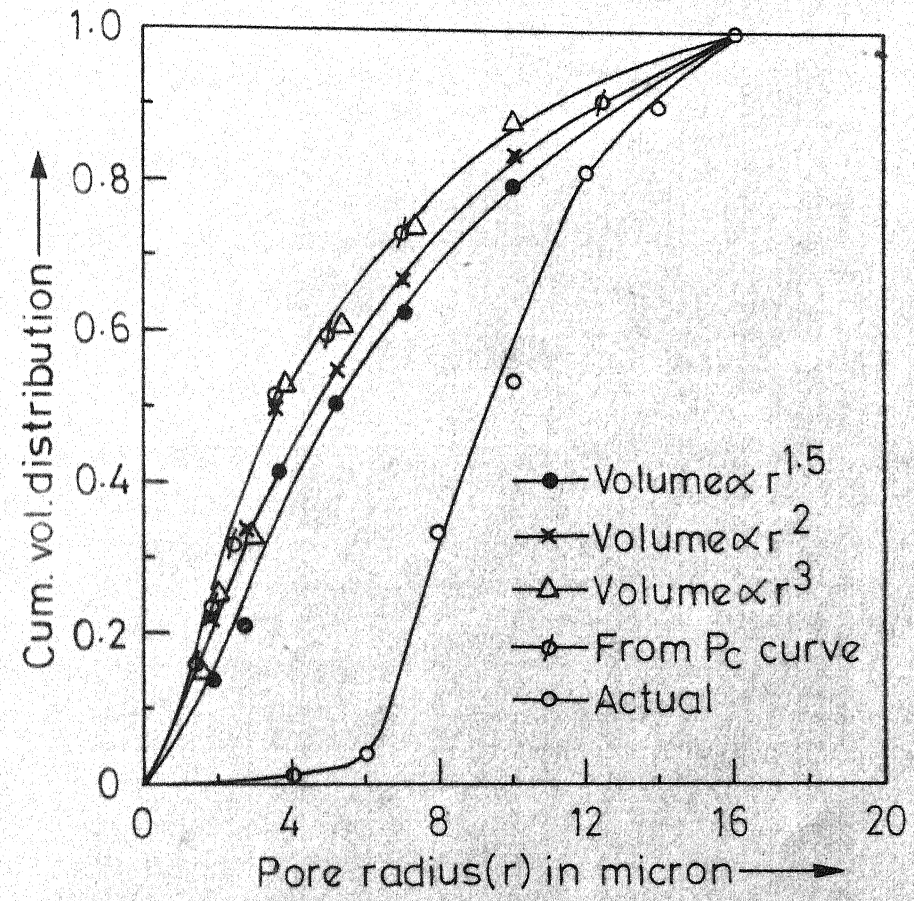


Fig.3b- Correction in volumetric distribution by Meyer's method. Network II.

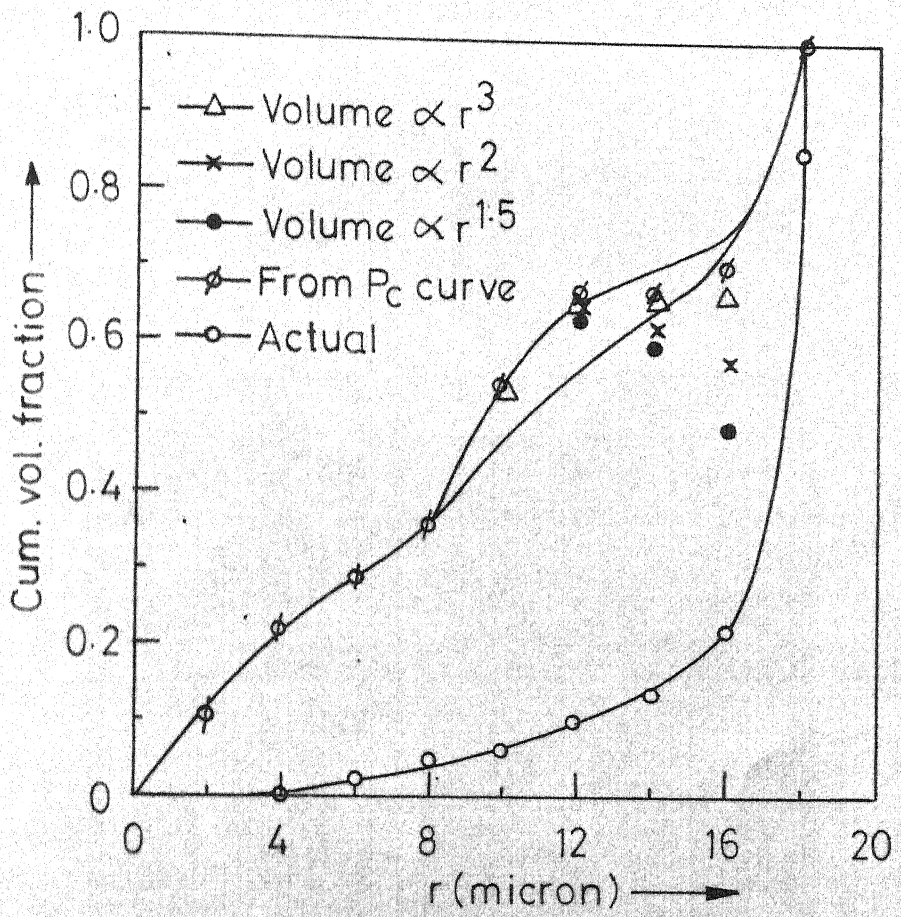


Fig. 3c - Correction in volumetric distribution by Meyer's method. Network III.

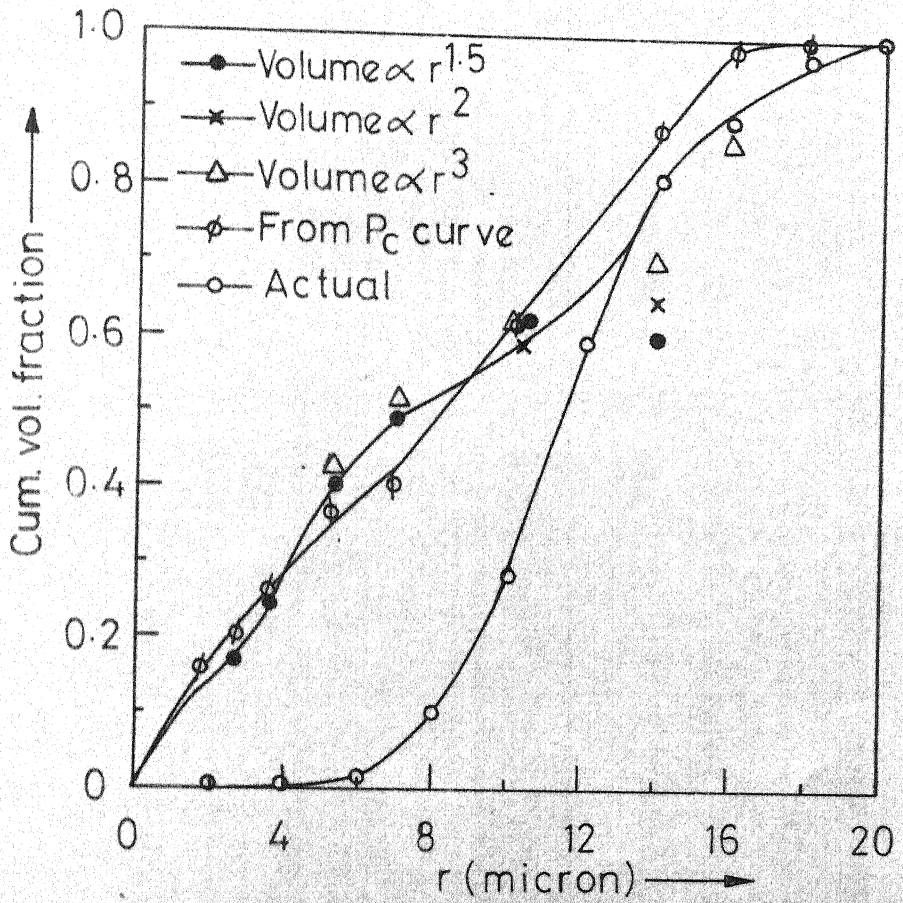


Fig. 3d - Correction in volumetric distribution by Meyer's method. Network IV.

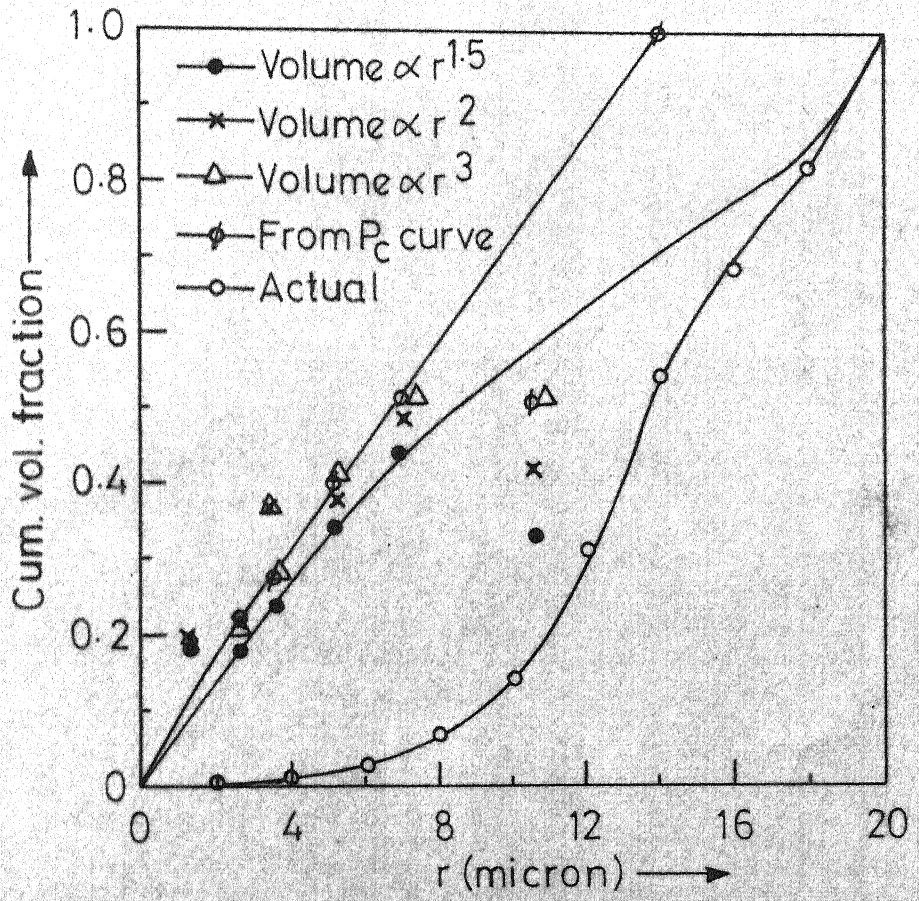


Fig. 3e-Correction in volumetric distribution by Meyer's method. Network V.

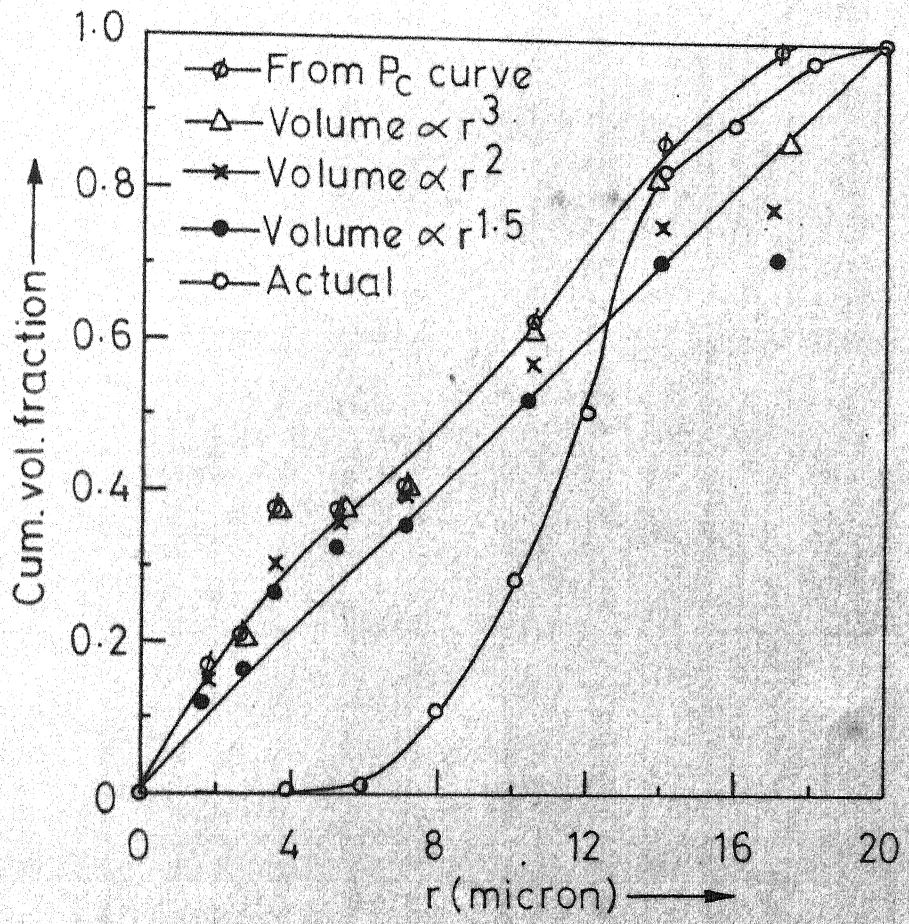
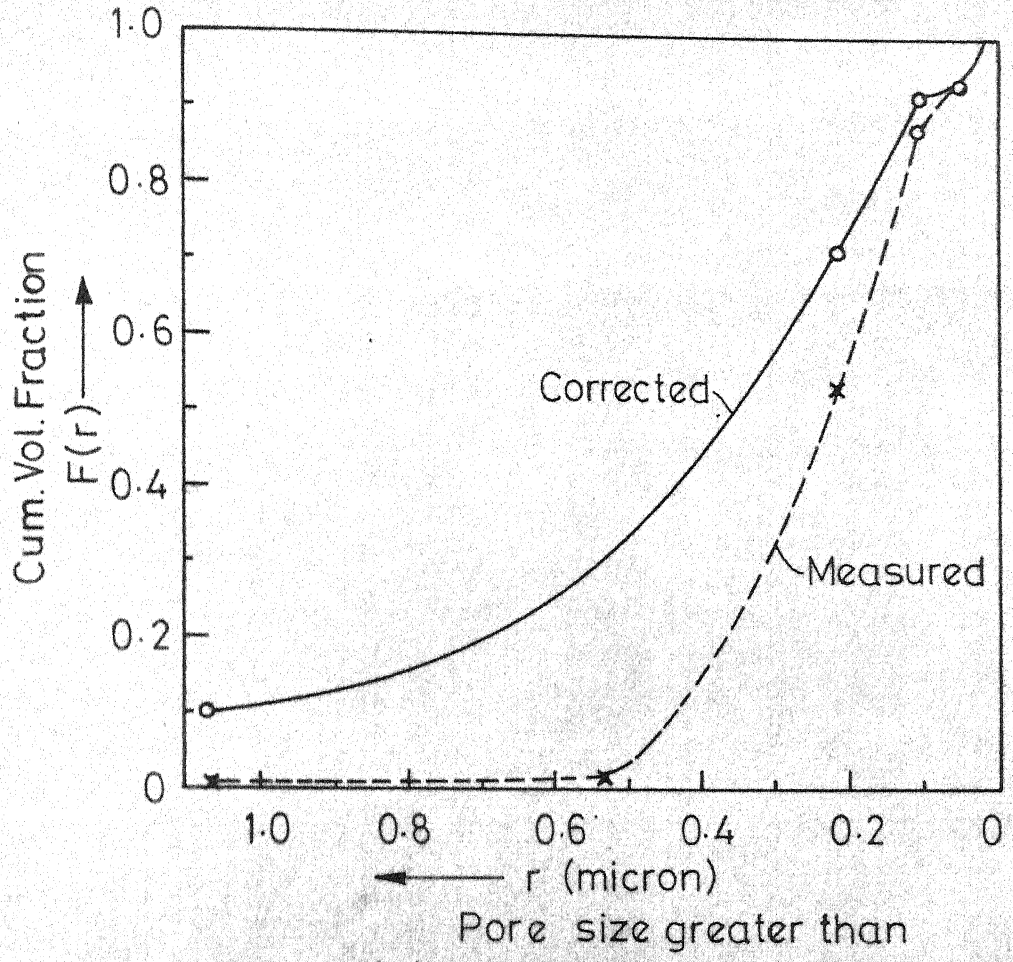
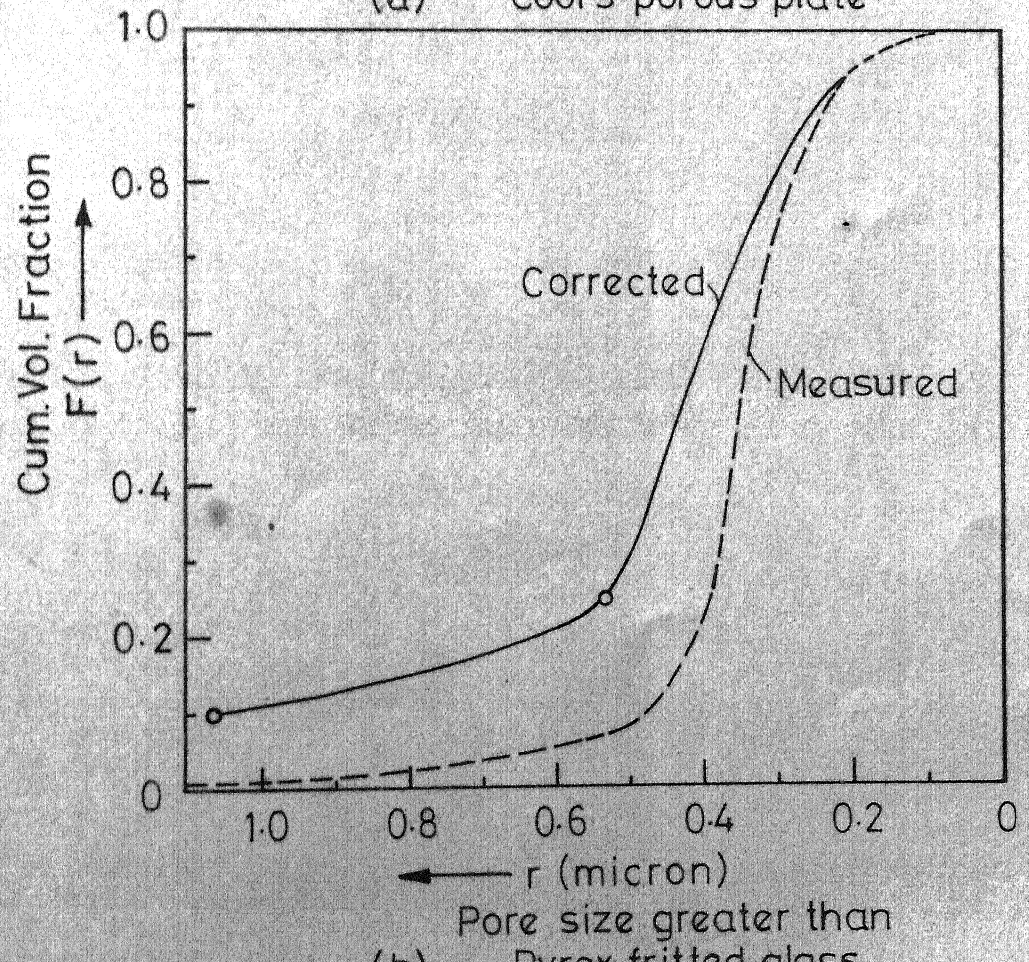


Fig. 3f - Correction in volumetric distribution by Meyer's method. Network VI.

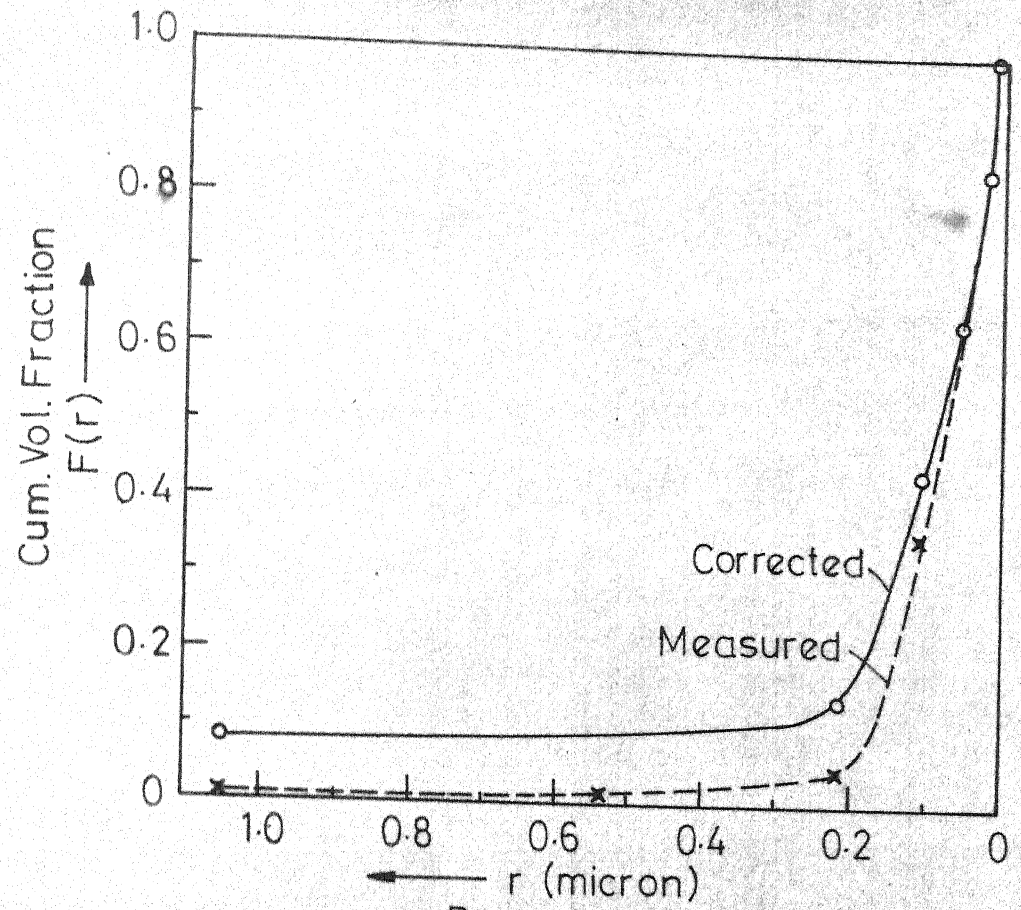


(a) Coors porous plate

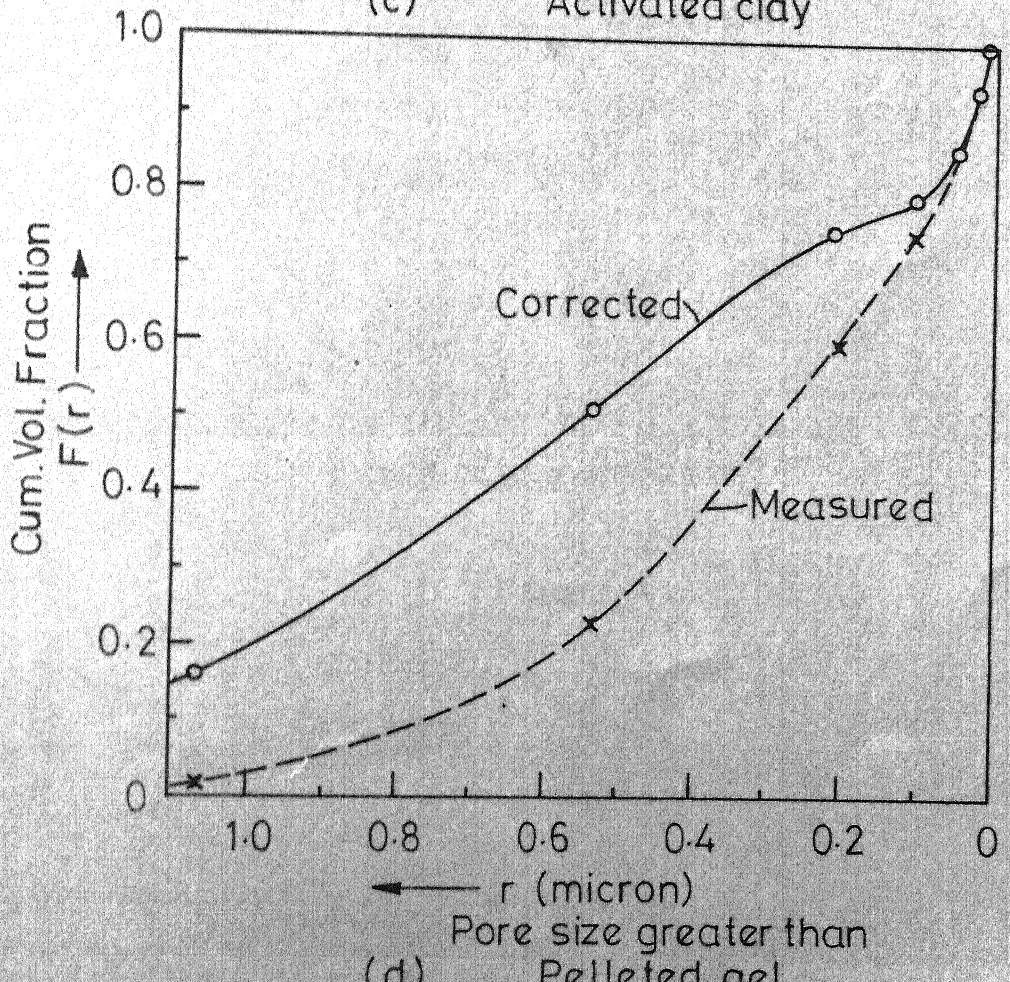


(b) Pyrex fritted glass

Fig. 4 -Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.



(c) Activated clay



(d) Pelleted gel

Fig. 4 - Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.

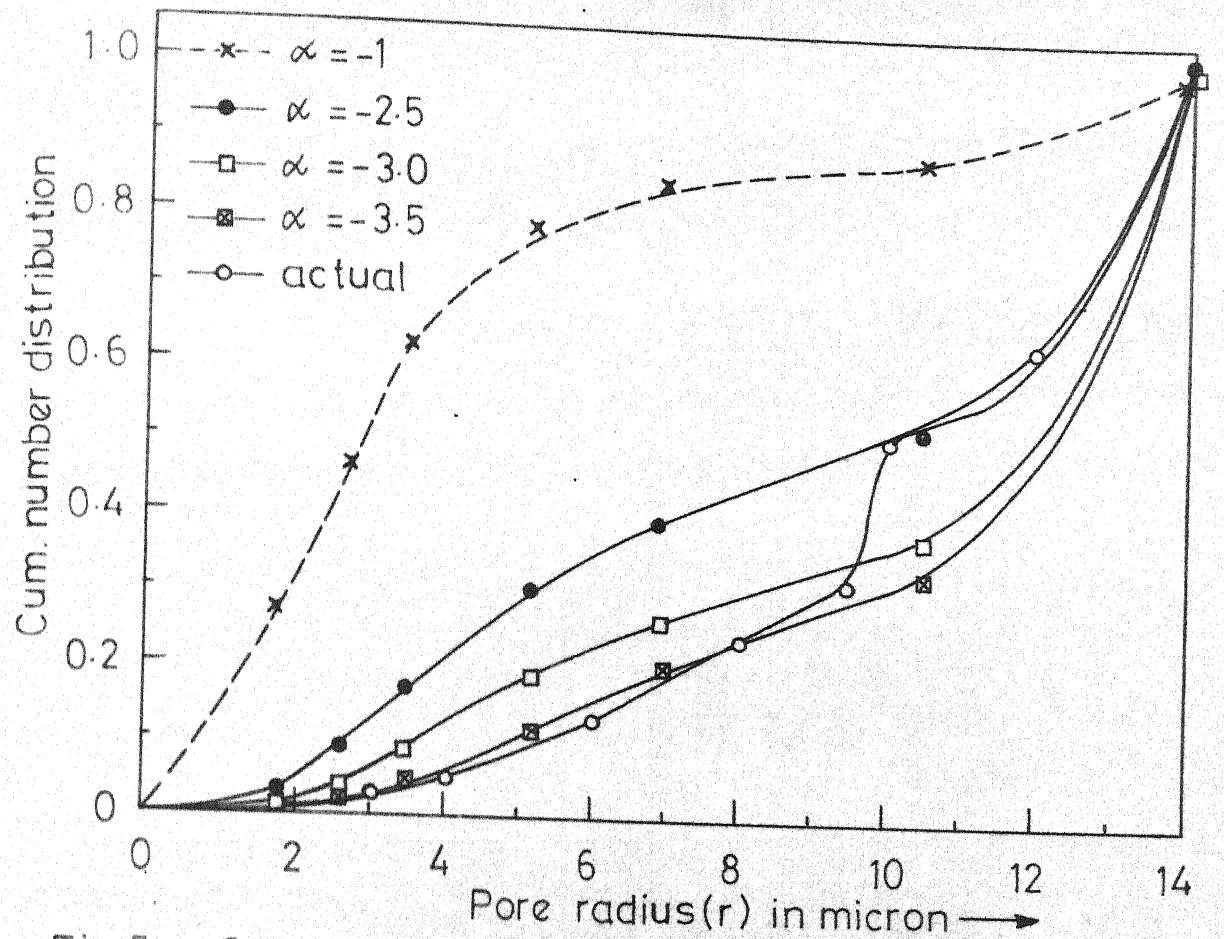


Fig. 5a - Comparison of calculated number distribution with actual network Fig. 1a.

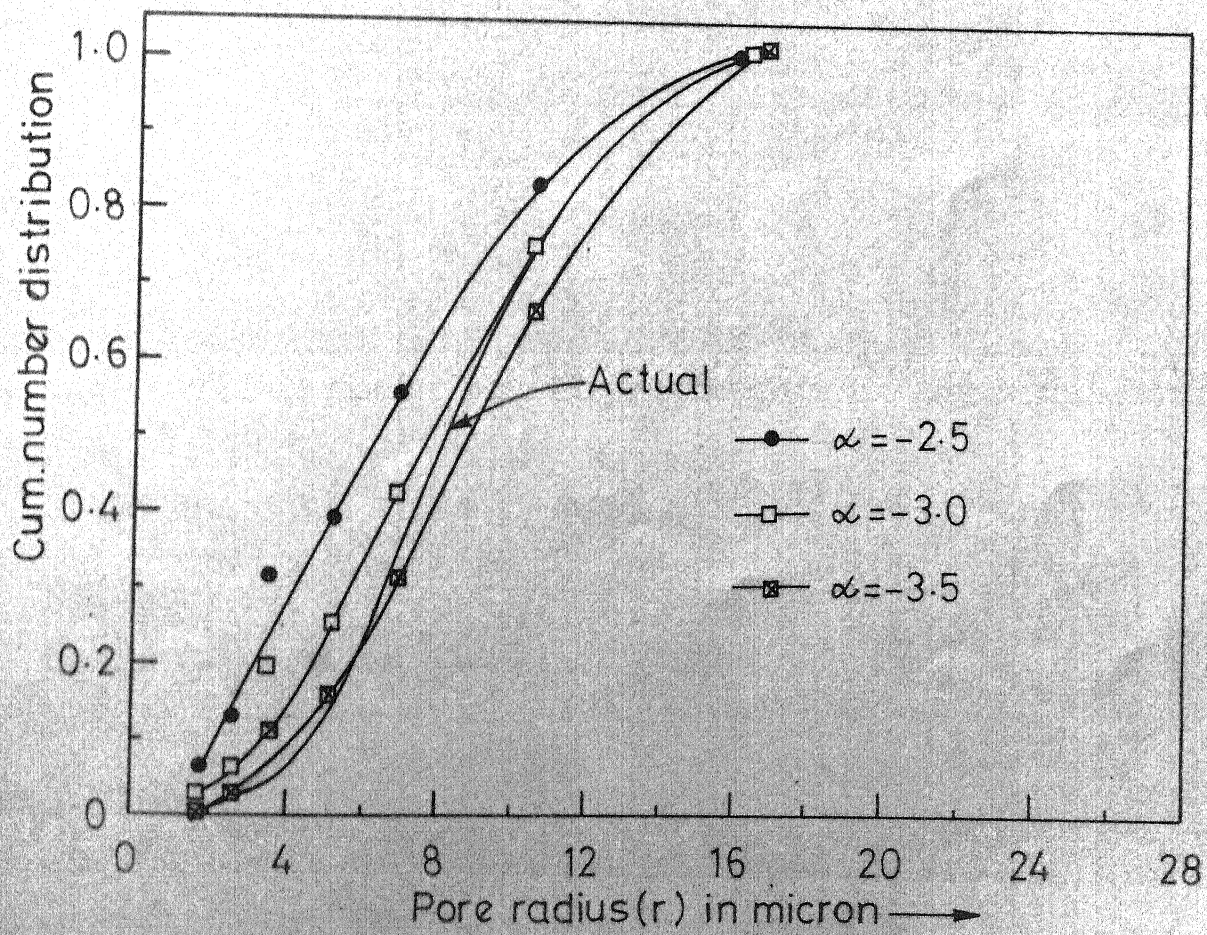


Fig. 5b - Comparison of calculated number distribution with actual Network Fig 1b

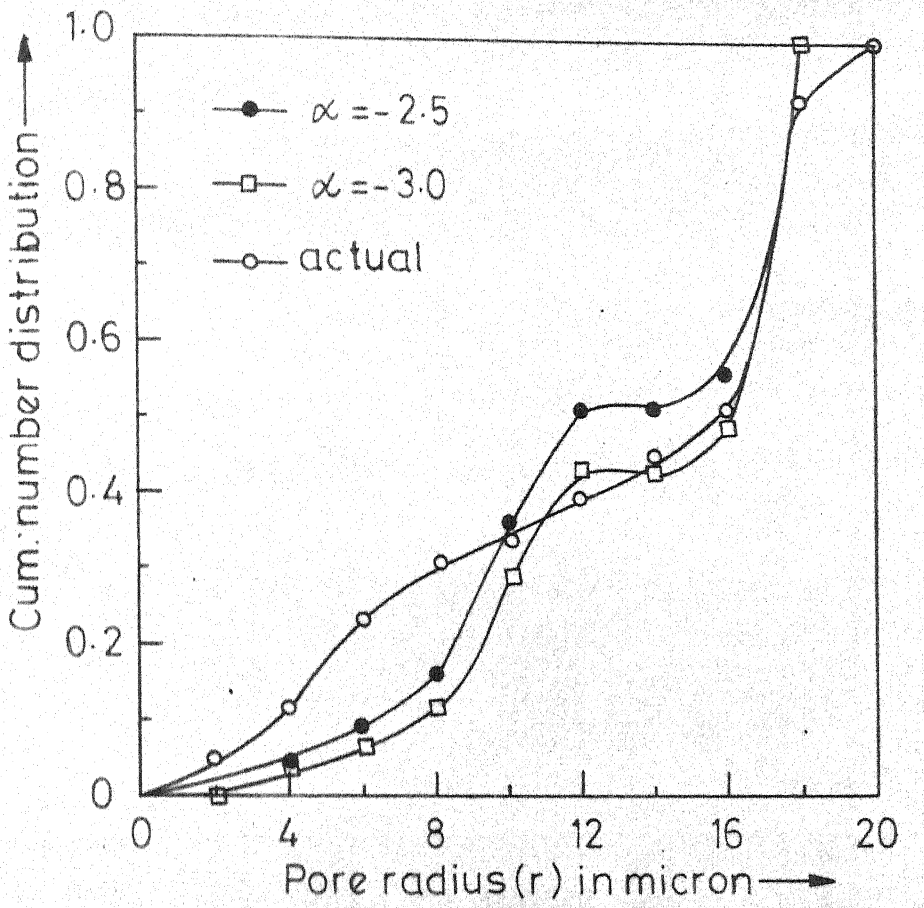


Fig.5 c - Comparison of calculated number distribution with actual. Network Fig.1c.

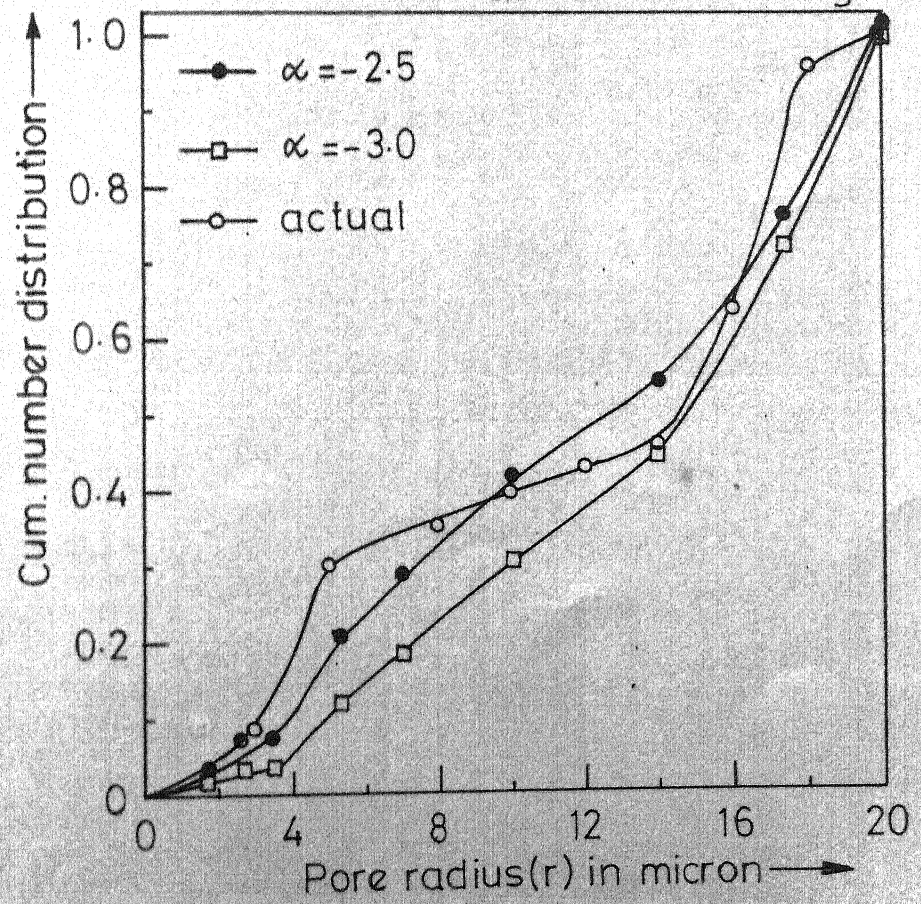


Fig.5 d - Comparison of calculated distribution with actual. Network Fig.1d.

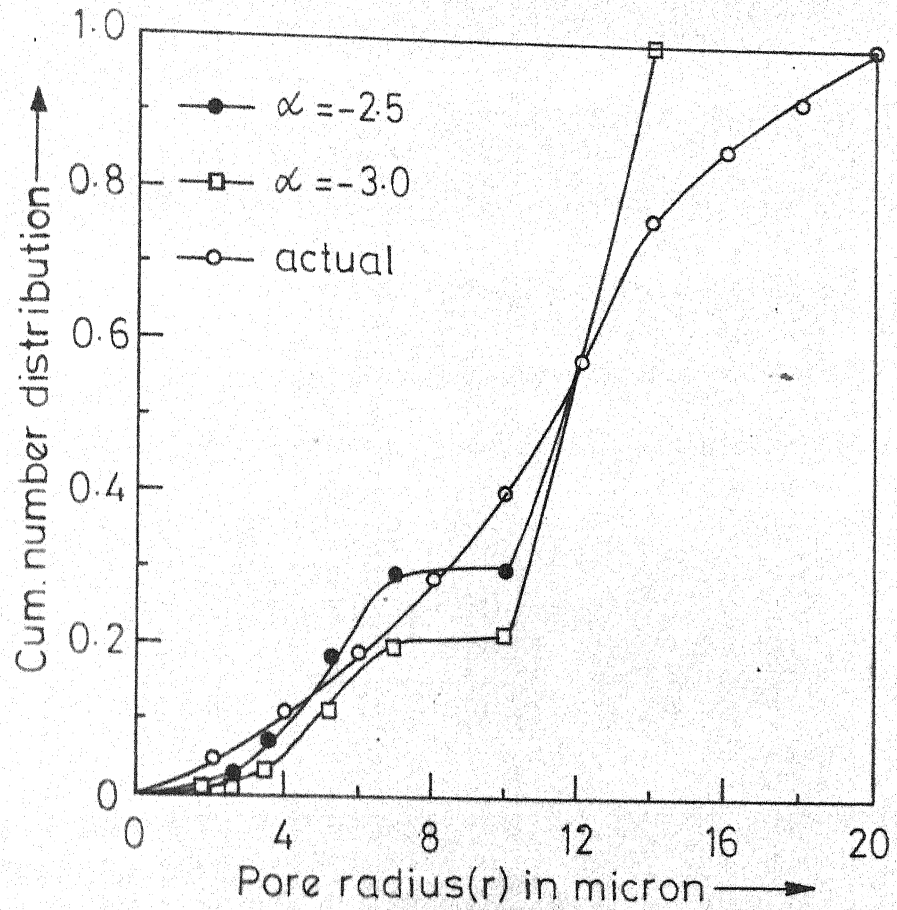


Fig. 5e-Comparison of calculated number distribution with actual. Network Fig.1e.

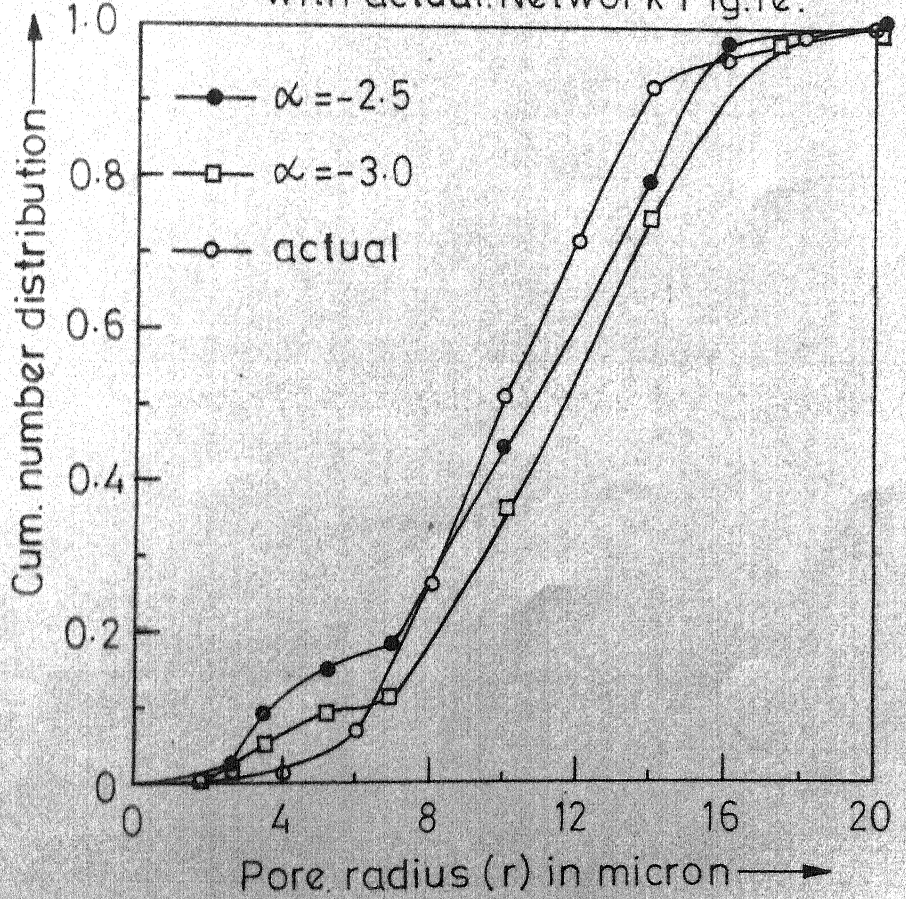


Fig.5 f-Comparison of calculated number distribution with actual. Network Fig.1 f.

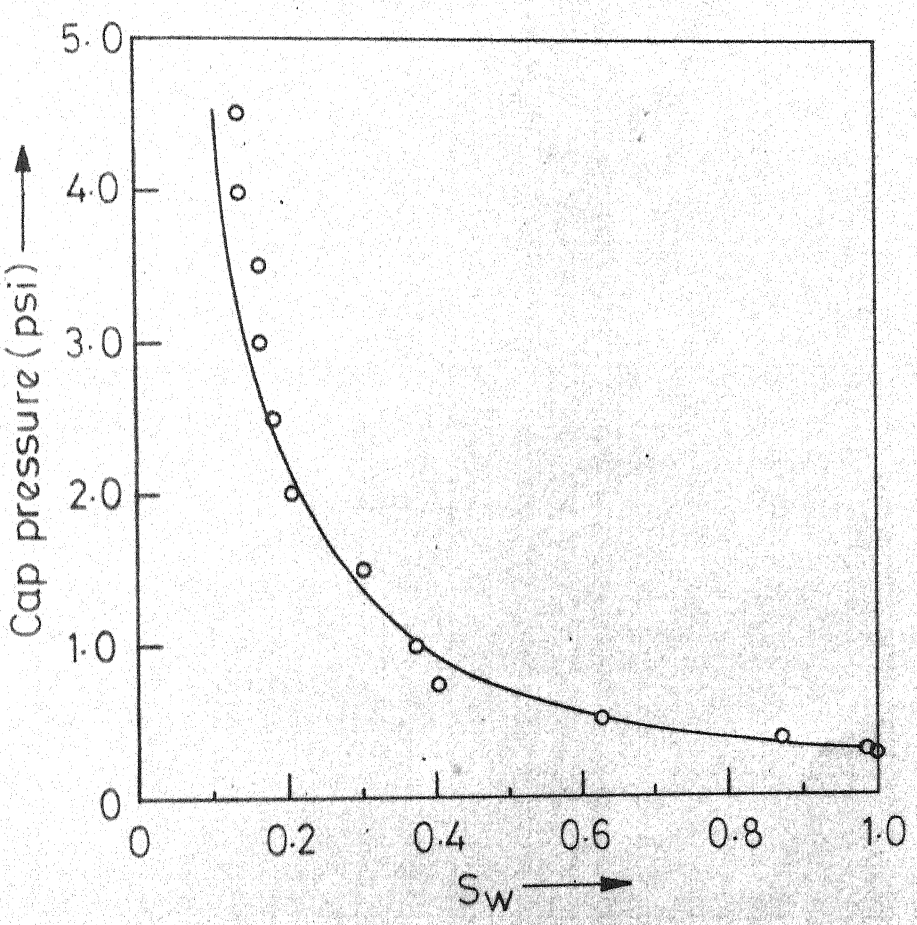


Fig. 6 - Least square fit of P_c data.
Network VI.

TABLE 1

INPUT DATA FOR NETWORK I

Network size	8 x 6 node points
Grid Spacing	112 μ
Average opening at node points	25 μ
Interfacial tension	20 dynes/cm
Contact angle (non wetting fluid)	180°
Viscosity(non wetting fluid)	0.8 C_p
Viscosity (wetting fluid)	1.0 C_p
Trapping factor	0.20
Time Step (initial)	200 μ sec.

Pore Size Distribution:

Radius (μ)	Cum. Fraction (intended)	Cum. Fraction (adjusted)
0	0	0.25
3	0.0175	0.26328
4	0.047	0.28535
6	0.137	0.35234
8	0.27	0.45235
9.5	0.362	0.52189
10	0.576	0.68234
12	0.628	0.72150
14	1.0	1.0

***

TABLE 2

ARBITRARY DISTRIBUTION USED IN SIMULATION OF NETWORKS

Network	Fore-Size (μ)	Cum. Number Distribution
III	0.0	0.0
	2.0	0.0434
	4.0	0.1304
	6.0	0.2608
	8.0	0.3478
	10.0	0.3912
	12.0	0.4346
	14.0	0.4780
	16.0	0.5650
	18.0	0.9130
	20.0	1.0
IV	0.0	0.0
	3.0	0.075
	5.0	0.325
	8.0	0.400
	10.0	0.450
	12.0	0.500
	14.0	0.550
	16.0	0.650
	18.0	0.950
	20.0	1.0

****

TABLE 3

CAPILLARY PRESSURE DATA FOR SOME POROUS MATERIALS[25]

Materials	Volume of mercury(cc) injected per gm. of sample at pressure (psi)						
	100	200	500	1000	2000	5000	10,000 (Macro pore vol.)
Coors Porous Plate	0.001	0.003	0.093	0.152	0.162	0.172	0.173
Pyrex Fritted Glass	0.001	0.012	0.159	0.168	0.169	0.169	0.169
Activated Clay	0.001	0.002	0.009	0.071	0.123	0.166	0.195
Pelleted Gel	0.003	0.040	0.108	0.133	0.152	0.168	0.178

TABLE 4

COMPARISON OF EXPERIMENTAL PORE-SIZE DISTRIBUTION OBTAINED FROM MERCURY POROSIMETRY TO THAT CORRECTED BY MEYER'S METHOD

a) Coors Porous Plate

Pore-Size(Micron) Greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.00578	0.09797
0.533	0.01734	0.03578
0.213	0.53757	0.71379
0.1066	0.87861	0.92197
0.053	0.93642	0.93954
0.021	0.99422	0.99422
0.01060	1.00000	1.00000

b) Pyrex UF Fritted Glass

Pore-Size (Micron) Greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.00592	0.10029
0.533	0.07101	0.24686
0.213	0.94083	0.94083
0.1066	0.99408	0.99408
0.05331	1.00000	1.00000
0.02132	1.00000	1.00000
0.01060	1.00000	1.00000

Table 4 (contd).

c) Activated Clay:

Pore-Size (Micron) Greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.00513	0.08693
0.533	0.01026	0.01604
0.213	0.4615	0.14971
0.1066	0.36410	0.44945
0.05331	0.63077	0.63897
0.02132	0.85128	0.85128
0.01060	1.00000	1.00000

d) Pelleted Cel:

Pore-Size (Micron) Greater than Equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.1685	0.16701
0.533	0.22472	0.51417
0.2132	0.60674	0.75752
0.1066	0.74719	0.79563
0.05231	0.85393	0.85803
0.02132	0.94382	0.94382
0.01060	1.00000	1.00000

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	1.0	5.16	0.5956	0.594	0.542	0.500
	1.5	3.46	0.5261	0.5261	0.500	0.420
	2.0	2.60	0.3181	0.3181	0.282	0.2003
	3.0	1.73	0.2354	0.2354	0.221	0.1373
	4.0	1.29	0.2226	0.2226	0.202	0.1273
III	0.259	20.00	1.0	1.0	1.0	
	0.287	18.00	1.0	1.0	1.0	
	0.323	16.00	0.7016	0.664	0.573	0.490
	0.370	14.00	0.6655	0.661	0.622	0.600
	0.430	12.00	0.6655	0.665	0.649	0.630
	0.516	10.00	0.5383	0.539	0.534	-
	0.646	8.00	0.3541	0.3541	0.354	0.347
	0.862	6.00	0.2829	0.2829	0.283	0.271
	1.290	4.00	0.2213	0.2213	0.221	0.220
	2.580	2.00	0.1015	0.1015	0.101	0.101
	2.58	2.00	0.1015			
	3.00	1.73	0.1015			

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
IV	0.259	20.00	1.0	1.0	1.0	1.0
	0.300	17.4	0.8657	-	-	-
	0.370	14.00	0.7195	0.702	0.649	0.602
	0.50	10.5	0.6296	0.630	0.612	0.585
	0.75	6.9	0.5143	0.5143	0.512	0.495
	1.0	5.16	0.4307	0.4307	0.428	0.409
	1.5	3.46	0.2650	0.2650	0.2650	0.255
	2.0	2.6	0.2603	0.2603	0.260	0.242
	2.5	-	0.1936	0.1936	0.192	0.170
	3.0	1.73	0.1936	0.1936	0.191	0.166
	3.5	-	0.1831	0.1831	0.18	0.154
	4.0	1.29	0.1400	0.1400	1.33	0.110
V	0.30	17.4	1.0			
	0.37	14.0	1.0	1.0	1.0	1.0
	0.50	10.5	0.5186	0.505	0.421	0.331
	0.75	6.9	0.5081	0.5074	0.479	0.438
	1.0	5.16	0.4032	0.4032	0.380	0.343
	1.5	3.46	0.2763	0.2763	0.269	0.234

Table 5 (contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2.0	2.6	0.2206	0.2206	0.210	0.171
	3.0	1.73	0.1900	0.1900	0.190	0.190
	4.0	1.29	0.1724	0.1724	0.172	0.172
VI	0.259	20.00	1.0	1.0	1.0	1.0
	0.30	17.4	0.9882	0.852	0.777	0.717
	0.37	14.0	0.8718	0.812	0.751	0.707
	0.50	10.5	0.6216	0.617	0.570	0.520
	0.75	6.9	0.4009	0.401	0.390	0.352
	1.0	5.16	0.3703	0.3703	0.358	0.322
	1.5	3.46	0.3702	0.3702	0.298	0.267
	2.5	2.6	0.2077	0.2077	0.202	0.163
	3.0	1.73	0.1653	0.1653	0.155	0.116
	4.0	1.29	0.1352	0.1352	0.122	0.089

TABLE 6

CALCULATION OF NUMBER CUM. DISTRIBUTION FROM P_c DATA OF NETWORKS BY FATT'S MODEL WITH MODIFIED EXPONENT

Network	P_c	r	S_w	Computed Number Distribution		
				α = -2.5	α = -3.0	α =-3.5
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	0.37	14.00	1.0	1.0	1.0	1.0
	0.50	10.5	0.6920	0.5247	0.3854	0.33
	0.75	6.9	0.5948	0.3962	0.26236	0.201
	1.00	5.16	0.5155	0.3086	0.1883	0.116
	1.50	3.46	0.3685	0.1716	0.0904	0.047
	2.0	2.60	0.2603	0.0310	0.011	0.0044
II	0.324	16.0	1.0	1.0	1.0	1.0
	0.5	10.5	0.91	0.831	0.752	0.667
	0.75	6.9	0.729	0.558	0.424	0.313
	1.0	5.16	0.596	0.390	0.258	0.161
	1.5	3.46	0.526	0.315	0.195	0.112
	2.0	2.6	0.318	0.130	0.064	0.029
	3.0	1.73	0.235	0.067	0.027	0.010
III	0.287	18.00	1.0		1.0	1.0
	0.323	16.00	0.70		0.485	0.560
	0.370	14.00	0.666		0.43	0.510
	0.430	12.00	0.666		0.43	0.510
	0.516	10.00	0.538		0.287	0.358

Table 6(contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	0.646	8.00	0.354		0.1184	0.16
	0.862	6.00	0.283		0.0678	0.090
	1.290	4.00	0.221		0.0365	0.042
	2.580	2.00	0.1015		0.0	0.0
IV	0.259	20.00	1.0	1.0	1.0	
	0.30	17.4	0.8657	0.76	0.72	
	0.37	14.0	0.7195	0.54	0.44	
	0.5	10.5	0.6296	0.418	0.305	
	0.75	6.9	0.5143	0.286	0.180	
	1.0	5.16	0.431	0.204	0.118	
	1.5	3.46	0.265	0.07	0.030	
	2.0	2.6	0.260	0.067	0.029	
	3.0	1.73	0.194	0.027	0.010	
V	0.37	14.0	1.0	1.0	1.0	
	0.50	10.5	0.5186	0.215	0.30	
	0.75	6.9	0.5081	0.202	0.29	
	1.00	5.16	0.4032	0.116	0.182	
	1.50	3.46	0.2763	0.035	0.07	
	2.0	2.6	0.2206	0.0128	0.03	
	3.0	1.73	0.190	0.0043	0.0115	

Table 6 (Contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
VI	0.259	20.0	1.0	1.0	1.0	
	0.30	16.0	0.988	0.98	0.977	
	0.37	14.0	0.8718	0.795	0.746	
	0.50	10.5	0.6216	0.4428	0.360	
	0.75	6.9	0.4009	0.1818	0.1144	
	1.00	5.16	0.3703	0.1514	0.091	
	1.50	3.46	0.3029	0.095	0.054	
	2.0	2.6	0.2077	0.0275	0.017	
	3.0	1.73	0.1653	0.002	0.0056	

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APPENDIX A

NETWORK MODEL: FLOW COMPUTATION

Pressure Computation:

Assuming that flow in the pore channels of a porous system is essentially viscous in nature (Re $\lesssim$ 75), Poiseuille's law of viscous flow could be applied for flow computation in each tube of the network. For single phase flow in a cylindrical tube of length l_i and radius r_i, the expression for flow rate, q_i is given as:

$$q_i = \frac{\pi r_i^4}{8\mu} \cdot \frac{\Delta P}{l_i} \qquad (A.1)$$

or

$$q_i = K_i \ \Delta P_i$$

where ΔP_i is the pressure differential causing flow in the ith tube. For multiphase flow K_i and ΔP_i may be modified depending upon the relative proportion of the different fluids present and the nature of the flow regime respectively. Knowing total fluid conductivity, K_i, of each tube and maintaining total volumetric balance a Kirchoff type equation can be written for each node point of the network:

$$\sum_{\substack{s=1,8 \\ k=i-1,i+1 \\ l=j-1,j+1 \\ (i,j)\neq(k,l)}} K_s \left[(P_{i,j} - P_{k,l}) + P_c \right] = 0 \qquad (A.2)$$

Knowing the values of K_s, P_c and the pressure at the boundaries, the set of simultaneous algebraic equations can be solved by Gauss-elimination technique.

Capillary Pressure:

Capillary pressure, P_c, is applicable only to those pores which undergo displacement flow. For single phase, slug or annular flow regimes, capillary pressure is essentially zero. In this computation P_c is taken as equal to the pressure required to squeeze an fluid/fluid interface from a mode point opening (radius r_{no}) to a tube of radius r_i (r_{no} r_i). For a tube of triangular cross-section

$$P_c = 1.78\ \gamma \cos\theta \left(\frac{1}{r_{no}} - \frac{1}{r_i}\right) \qquad (A.3)$$

where γ = interfacial tension and θ is the contact angle which in our case is the receding contact angle.

Flow Behaviour in a Single Tube:

i) Single Phase Flow:

The total volumetric flow rate through a tube of triangular (equilateral) cross section, with the radius of the inscribed circle, r, viscosity of the fluid μ, and pressure gradient $\Delta P/\Delta l$, is

$$q = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu} \frac{\Delta P}{\Delta l} \qquad (A.4)$$

ii) Annular Flow:

We used modified Yuster relationship as suggested

by Singhal[22] for flow computation.

$$q_w = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_w} \frac{\Delta P}{\Delta l} S_w^2 \qquad (A.5)$$

$$q_n = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_n} \frac{\Delta P}{\Delta l} \left[\left(2S_n \frac{\mu_n}{\mu_w} + S_n^2 \left(1 - 2 \frac{\mu_n}{\mu_w}\right)\right)\right] \qquad (A.6)$$

where S denotes saturation and subscripts w and n denote wetting and and non-wetting phase respectively.

(iii) Slug Flow:

Total flow rate is given by

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n + 6a\mu_w)} \Delta P \qquad (A.7)$$

where a is the side of the triangular cross section.

(iv) Displacement Flow:

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n)} \left[\Delta P \pm P_c\right] \qquad (A.8)$$

Selection of Tube for Flow Change:

Depending on the availability of fluids at a node point, transition between flow regimes will occur. In many instances, channels leaving a node point may be capable of carrying more of a particular phase (fluid) than is available at that time. In such cases, saturation and flow regime changes in the tubes will have to occur to unload all available fluids. A table of possible transition between flow regimes is given in Table A-1. Some times there may exist more than one pore which might be undergoing flow in the regime to be altered. Selection of tubes

for flow changes in such cases is done by Monte-Carlo method with a bias for flow capacities of the competing tubes.

General Scheme for Flow Computation:

Words in block capital letters are subroutine name referred to in the program listing.

The network is generated in the program by SIMU with specified pore-size distribution and grid size. This subroutine also computes the volume of the pores connected to each node point and flow conductivities to the two fluids. Other data; fluid viscosities, interfacial tension, pressure differential across the model and contact angle, are read in the main program CALC. The radius of the opening at the node points, r_n, is chosen to be slightly larger than the largest tube radius of the network.

The next step is to determine the pressure distribution in the model. Pressure at each node point is computed by solving the system of equation A-2 by PRSOL through SOLVE. Apart from updating the conductivities of each tube after every time step, SOLVE also immobilizes those tubes which may cause outflow from the first row and inflow from the last row. Also, those tubes, whose capillary pressure is greater than the pressure differential available and are oppositely directed, are blocked by the action of trapping factor. When a tube is blocked its conductivity is set equal to zero and the system of equations A-2 is solved. This is repeated till no more

tubes are blocked. While calculating P_c for tubes in the first row, the node point opening is assumed to be infinite. For other rows the specified value of r_n is used for the calculation.

The total outflow of each phase (fluid) from each node point is calculated under the existing pressure distribution by FLOW. Outflow from a tube is entered as inflow to the connected node point by COND(1). The imbalance between inflow and outflow of a particular phase at a node point is corrected by CHANGE which also effects the flow changes necessary for this correction. The capillary pressure and flow conductivities for the corrected flow distribution is computed by COND(2) and stored. Outflow from the model is obtained by adding together the inflow to the last row of node points. The volume of the fluid left in the model is computed to evaluate the saturation. This process is repeated till the equilibrium wetting phase saturation in model is obtained for that pressure drop.

Steps of Computation:

(i) Call SIMU to simulate the network model. Assign tube sizes, locations etc. Calculate the volume of each tube, its conductivity to displacing and displaced fluids.

(ii) Call SOLVE to update the conductivities through COND(2) and solve the system of equations A.2 by PRSOL to evaluate the absolute pressure at each node point. In case some of the tubes are blocked, call COND(1) to zero the

conductivity of those tubes and again call PRSOL to solve the systemof equation A-2. Repeat till no more tubes are blocked.

(iii) Choose node points in descending order of absolute pressure and call FLOW to calculate outflow of each fluid from each tube and node point.

(iv) Calculate imbalance at each node point to test whether overall material balance of incoming and outgoing fluids is satisfied.

(v) Imbalance in the material balance of each phase is removed by assigning the excess incoming phase to various tubes by Monte Carlo method through CHANGE without forcing flow change in the tubes.

(vi) Assign outflow from each tube as the inflow to the connected down-stream node points.

(vii) In case of back flow, calculate inflow to those tubes and node points in FLOW. If there is any imbalance either in total fluid at the connected node points or imbalance in any phase in any tube, call CHANGE to assign the differential volume to various tubes.

(viii) Calculate outflow from the model by adding the inflow to each node points in the last row of the network.

(ix) Calculate total fluid volume left in the model by adding the volume of the fluid in each tube at the end of the time interval.

(x) Calculate the saturation for each phase.

(xi) Repeat steps (i) to (x) till there is practically no change in the total outflow from the model in the successive time steps (less than 1% of the outflow in the first time step) for the same ΔP.

(xii) Test whether the sum of the cumulative outflow and the volume of fluid remaining in the network for each fluid at the end of every time step is constant.

(xiii) Repeat the sequence of operations with higher ΔP, to get the value of equilibrium S_w (wetting phase saturation) for different P_c. Thus P_c curve is generated.

TABLE A-1

TRANSITION BETWEEN FLOW REGIMES

Flow Regimes To / From	Single Phase	Displacement	Slug	Annular
Single Phase	x	1*	1*	1
Displacement	2	x	-	-
Slug	-	-	x	1
Annular	-	1**	1	1

x No change in flow regimes.

1 Easy transition.

2 Transition influenced by capillary forces.

- Transition not possible without going through other flow regimes.

* Modified single phase flow for non-wetting flow because of a film of wetting fluid at the pore walls.

** Possible only for non-wetting phase displacing the wetting phase.

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APPENDIX B

MEYER'S METHOD

The radius r of a pore is defined to be equal to the radius of a capillary tube which will just allow mercury to enter it against capillary force at the same pressure as that at which the pore will fill, if connected to a mercury source.

Let $\lambda(r)$ be the fraction (volumetric) of the total void space occupied by r-pores i.e. pores whose radii lie in the range r to r+dr. The number of such r pores in a unit volume will be given by

$$a(r)\,dr = \frac{f\,\lambda(r)}{Kr^3} \qquad (B.1)$$

where f = fractional porosity

Kr^3 = vol. of a single pore of radius r

It is necessary to designate one representative point in the interior of each pore which we shall term "centre of the pore". For our purpose, any point will do so long as it is not too close to the wall of the pore and is consistently chosen, e.g. cg. of the void space will serve. Also, we define a volume dv so small that the probability of the centres of two or more r-pores being located in this volume may be neglected.

Let the probability of m r-pores being located in any volume v be $\psi_m(v,r)dr$. Then for randomly distributed pores

$$\psi_m\ (v+dv,r)\ dr = \psi_m(v,r)dr\ [1 - (adr)\ dv] + \psi_{m-1}(v,r)dr\ (adr)dv \qquad (B.2)$$

which on re-arranging gives

$$\frac{d(\psi_m\ dr)}{dv} = \frac{[(a\ dr)v]^m}{m!}\ \exp[-(adr)\ v] \qquad (B.3)$$

Now we define a volume $v(r_o,r)$ such that, if an r-pore is located in $v(r_o,r)$, it may be expected to be connected to an r_o-pore. This can be done if we assume that two pores are connected if the centre of the smaller lies in a volume adjacent to the larger pore, which is the difference between the volume of a pore whose radius equals the sum of the radii of the two pores minus the volume of the larger pore i.e. for $r_o > r$

$$v(r_o,r) = K(r_o+r)^3 - Kr_o^3 = K(3r^2\ r_o + 3r\ r_o^2 + r^3) \qquad (B.4)$$

Now if in Eq.(B-3) v is replaced by $v(r_o,r)$, we get the probability of m r-pores all being joined to the same r_o-pore. The probable number of such groups of pores which would exist in a unit volume would be given by the product of this probability times the number of $v\ (r_o,r)$ volumes in a unit cube (which is equal to the number of r_o pores in a unit cube). This number is equal to

$$a(r_o)dr\ \psi_m\ (v(r_o,r),r)\ dr$$

or $$a(r_o)dr\ \psi_m\ (r_o,r)\ dr$$

We are here interested in $\psi_o(r_o,r)dr$ which is the probability of an r_o pore not being connected to an r-pore.

Let a porous rock be subjected to mercury pressure such that all pores of radius $\geq$ r would fill if they had access to mercury, and let $\Gamma(r)$ be the measured fraction of the pore volume that is filled up with injected mercury at that pressure. Let $\Theta(r)$ be the actual fraction of the pore-volume devoted to pores of radius $\geq$r.

If the simplifying assumption is made that only pores of radius $\geq$ r which will fail to fill are those that are not connected to any other pores of equal or larger radius. That is the probability of an r_o pore failing to fill is given by the multiplicative law of probability $\int_r^\infty \psi_o(r_o,r)dr$.

The total number of pores of radius $\geq r_o$ which will fail to fill is given by the expression

$$\Psi(r_o,r) = \int_{r_o}^{\infty} a(r)dr \left\{ \int_r^\infty \pi\psi_o(r_o,r)\, dr \right\} \qquad (B.5)$$

$$\text{Hence } \Gamma(r) = \Theta(r)\left[1 - \frac{\Psi(r_o,r)}{\int_{r_o}^{\infty} a(r)dr}\right] \qquad (B.6)$$

This is the expression from which we shall obtain true pore-size distribution $\Theta(r)$ from the actual distribution $\Gamma(r)$.

Numerical Approximation:

Since the above expression is not convenient for numerical calculation the following approximation are used. The radius r

is discritized so that it takes only a finite number of values $r_n < r_{n-1} < \cdots\cdots < r_1$ and

$$\Delta r_i = r_{i-1} - r_i \qquad i = 1,2 \text{ -----}$$

$$a_i = \int_{r_i}^{r_{i-1}} a(r)\,dr$$

$$\gamma_i = \Gamma(r_i) - \Gamma(r_{i-1})$$

$$\nu_i = \Theta(r_i) - \Theta(r_{i-1})$$

$$\psi_{ij} = \exp\left[-a_i\, v(r_i, r_j)\right]$$

$$\Psi(r_i, r_j) = \sum_{k=1}^{i} a_k \prod_{l=1}^{j} \psi_{kl}$$

Substituting these expressions in Eq. (B.6) gives the approximate equation

$$\Gamma(r_i) = \sum_{k=1}^{i} \gamma_k = \sum_{k=1}^{i} \nu_k \times \left[1 - \frac{\sum_{k=1}^{i} a_k \prod_{l=1}^{j} \psi_{kl}}{\sum_{k=1}^{i} a_k}\right] \qquad \text{(B.6a)}$$

Algorithm:

(1) Assume a value of ν_i and calculate a_i and ψ_{ij}.

(2) Using these values solve Eq. (B.6a) for ν_i.

(3) If computed ν_i value is not close enough to the assumed value, make another assumption and repeat this process.

***

APPENDIX C

GLOSSARY OF TERMS USED

Porosity (f) is the ratio between the void space and bulk volume in a porous medium.

Capillary Pressure (P_c) is the difference in pressures across a fluid/fluid interface. Capillary pressure curve describes the changes in capillary (threshold) pressure of a porous as a function of its fluid saturation.

Threshold Pressure (P_T) is the minimum excess pressure must be maintained in the non-wetting phase to enable it enter a given porous medium.

Saturation(S) of any fluid in a porous medium is the ratio between the volume of the fluid in the medium to its pore volume.

Contact Angle (θ) is the angle (through the displacing phase) that the fluid/fluid interface makes with the surface of the porous medium.

Wetting Phase is the fluid in a porous medium whose contact angle with the solid surface is less than 90°. If the contact angle is more than 90° it is called non-wetting phase.

****

APPENDIX D

PROGRAM LISTING OF MEYER'S METHOD

N	Number of data in the set
SIGMA	Interfacial tension
THETA	Contact angle of non-wetting phase
POR	Porosity
R(I)	Pore-size corresponding to P(I)
PC	Capillary pressure
SGAMA	Cumulative Volumeof Mercury Injected.
ESTNU	Assumed value of nu
NU	Computed nu
DIFNU	Difference between estimated and computed nu
SV(I,J)	$v(r_i, r_j)$; characteristic volume
PSI(I,J)	ψ_{ij}
PSIR(I,J)	Ψ_i

FORTRAN SOURCE LIST

```
ISN       SOURCE STATEMENT

  0 $IBFTC MAIN
    C      MEYERS METHOD
    C       PC  IN  PSI
    C      CAT=1.0 MEANS THE USUAL VALUES OF CHANGE ARE NOT TO BE USED
  1        COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
  2        COMMON/A2/RS(20),RC(20),SIGMA
  3        COMMON/A3/NU(500) ,POR
  4        DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500),ESTNU(500)
  5        REAL NU
  6        READ 60,N
 10     60 FORMAT(I4)
 11        PRINT120
 12    120 FORMAT(1H1 )
 13        READ62,SIGMA,THETA
 14     62 FORMAT(5F10.3)
 15     65 FORMAT(5F10.5)
 16        THETA= THETA*3.1416/180.
 17        READ62,POR
 20        PRINT50,THETA
 21     50 FORMAT(5X,*THETA=*,F10.5)
 22        N=N+1
 23        DO12 I=2,N
 24        R(I)=0.0
 25        RS(I)=0.0
 26        RC(I)=0.0
 27        A(I)=0.0
 30        SUMA(I)=0.0
 31        DO 12 J=1,N
 32        SV(I,J)=0.0
 33        PSI(I,J)=0.0
 34        PSIR=0.0
 35     12 CONTINUE
 40        DO 101 IK=2,N
 41    101 READ65,P(IK),SGAMA(IK)
 43        PRINT20,(P(IK),IK=2,N),(SGAMA(IK),IK=2,N)
 54        DO 40 IM=2,N
 55     40 SGAMA(IM)=SGAMA(IM)/POR
 57        PRINT5
 60      5 FORMAT(5X,12HACTUAL VALUE ,10X,2HIK ,5X,10HTRUE VALUE  /)
 61        DO1C J=2,N
 62        CAT=0.0
 63        DIFNU(1)=0.0
 64        IK=2
 65        ESTNU(IK)=SGAMA(J)
 66      2 CALL SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,J,J)
 67        IF(IK.EQ.2.AND.J.EQ.2)PRINT20,(R(I),I=1,N)
 76        IF(IK.EQ.2.AND.J.EQ.2)PRINT20,((SV(I,IJ),IJ=2,N),I=2,N)
111     20 FORMAT(5X,8E15.8)
112        NU(IK)=SGAMA(J)/(1.-PSIR/SUMA(J))
113        DIFNU(IK)=NU(IK)-ESTNU(IK)
114        IF(DIFNU(IK).GT.0.0.AND.DIFNU(IK-1).LT.0.0)GO TO 25
117        IF(DIFNU(IK).LT.0.0.AND.DIFNU(IK-1).GT.0.0) GO TO 25
122        IF(ABS(DIFNU(IK)).LE.0.0002) GO TO 7
125        IF(CAT.EQ.1.0)GO TO 25
130        IF(ESTNU(IK).GT.0.0C01)CHANGE=0.0001
```

```
CGG145                                  FORTRAN SOURCE LIST MAIN
    ISN        SOURCE STATEMENT

    133        IF(ESTNU(IK).GT.0.001)CHANGE=0.001
    136        IF(ESTNU(IK).GT.0.01)CHANGE=0.01
    141        IF(ESTNU(IK).GT.0.1)CHANGE=0.1
    144        IF(ESTNU(IK).GT.0.9)CHANGE=0.005
    147        IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE
    152        IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE
    155        IK=IK+1
    156        IF(IK.GE.500) GO TO 7
    161        GO TO 2
    162     25 CHANGE=CHANGE/2.
    163        IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE
    166        IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE
    171        IK=IK+1
    172        CAT=1.0
    173        GO TO 2
    174      7 PRINT 6,SGAMA(J),IK,ESTNU(IK)
    175      6 FORMAT(5X,F10.5,10X, I5,5X,F10.5)
    176     10 CONTINUE
    200        PRINT8,(A(J),SUMA(J),J=2,N)
    205      8 FORMAT(10X,E15.7,10X,E15.7)
    206     22 STOP
    207        END
CGG145                                  IBMAP ASSEMBLY MAIN


  NO MESSAGES FOR ABOVE ASSEMBLY
```

CGG145 FORTRAN SOURCE LIST

```
ISN        SOURCE STATEMENT

  0 $IBFTC SUB1
  1        SUBROUTINE VOL(P,R,THETA,IK,N,SV,M,IM)
  2        COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
  3        COMMON/A2/RS(20),RC(20),SIGMA
  4        COMMON/A3/NU(500) ,FOR
  5        DIMENSION P(20),SV(20,20),R(20) ,A(20),DIFNU(500)
  6        FACTOR=1./68947.3*10.**4
  7        DO 1 I=2,N
 10        R(I)=FACTOR*2.*SIGMA*COS(THETA)/P(I)
 11        R(I)=ABS(R(I))
 12        RS(I)=R(I)**2
 13      1 RC(I)=R(I)**3
 15        R(1)=20.0
 16        RS(1)=R(1)**2
 17        N1=N+1
 20        DO 6 I=2,N
 21        DO 6 J=2,N
 22        IF(R(J).GT.R(I))GO TO 7
 25      5 SV(I,J)=2.*R(I)*R(J)+RS(J)
 26        GO TO 6
 27      7 SV(I,J)=2.*R(I)*R(J)+RS(I)
 30      6 CONTINUE
 33        DO10 I=2,N
 34        DO10 J=2,N
 35     10 SV(I,J)=ABS(SV(I,J))
 40        RETURN
 41        END
```

CGG145 IBMAP ASSEMBLY SUB1

NO MESSAGES FOR ABOVE ASSEMBLY

CGG145 FORTRAN SOURCE LIST

ISN SOURCE STATEMENT

```
      0 $IBFTC SUB2
      1       SUBROUTINE SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,IL,JK)
      2       COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
      3       COMMON/A2/RS(20),RC(20),SIGMA
      4       COMMON/A3/NU(500) ,FOR
      5       DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500) ,ESTNU(500)
      6       REAL NU
      7       CALL FLUN(99999)
     10       N1=N
     11       NU(IK)=ESTNU(IK)
     12       SUMA(1)=0.0
     13       IF(JK.EQ.2)CALLVOL(P,R,THETA,IK,N,SV,M,IM)
     16       I=IL
     17       A(I)=NU(IK)*(1./R(I)-1./R(I-1))*FOR
     20       DO 12 J=2,N1
     21       B=-A(I)*SV(I,J)
     22       IF(B.GE.88.0) GO TO 1
     25       IF(B.LE.(-88.0)) GO TO 2
     30       PSI(I,J)=EXP(B)
     31       GO TO 12
     32     1 CONTINUE
     33     3   PSI(I,J)=1.0E30
     34         GO TO 12
     35     2 CONTINUE
     36     4 PSI(I,J)=0.0
     37    12 CONTINUE
     41       J=JK
     42       DO 8 K=2,IL
     43       TEMP(I,J)=0.
     44       PROD=1.
     45       DO 10 L=2,JK
     46       DELTAR=R(L-1)-R(L)
     47       PROD=PROD*PSI(K,L)
     50       IF(PROD.LE.0.1E-37)PROD=0.0
     53    10 CONTINUE
     55     8 TEMP(I,J)=TEMP(I,J)+A(K)*PROD
     57       PSIR=TEMP(I,J)
     60     9 CONTINUE
     61       SUMA(I)=SUMA(I-1)+A(I)
     62     5 FORMAT(5X,8E15.7)
     63       RETURN
     64       END
```

CGG145 IBMAP ASSEMBLY SUB2

NO MESSAGES FOR ABOVE ASSEMBLY

CGG145 IBLDR -- JOB 000000

*** OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT 16 HRS. 21 MTS.

APPENDIX E

PROGRAM LISTING NETWORK MODEL

The first subscript in each variable in the program refers to the node point.

X(1) to X(8) The radii of the 8 tubes

X(9) to X(16) Length of the tubes

X(17) to X(24) Fluid content and flow regimes in the tubes

- 1.0 wetting (one phase flow)
- 2.0 non-wetting (one phase flow)
- 3.0 Displacement (non-wetting close to the node point)
- 3.5 Displacement (wetting closer to the node point)
- 4.1 Annular flow (displaced phase wetting)
- 4.2 Annular flow (displacing phase wetting)
- 4.5 Slug flow

X(25) to X(32) Flow or no flow situation

- 1.0 Flow occurring
- 2.0 Flow blocked
- 1.5 Flow provisionally blocked
- 2.5 Flow permanently blocked

X(33) to X(40) Flow conductivities of the tubes to displaced fluid

X(41) to X(48) Flow conductivities of the tubes to displacing fluid

X(49) to X(56) Volume of the tubes

X(57) to X(64) Displaced fluid content of the tube

X(65) to X(72)	Effective pressure drops across the tubes
X(73)	Incoming fluids
	1.0 displaced
	2.0 displacing
	3.0 Both
	4.0 none (node point isolated)
X(74)	Absolute pressure at node points
X(75) to X(82)	Appropriate conductivities of the tubes
X(83)	Volume of incoming displaced fluid
X(84)	Volume of incoming displacing fluid
X(85) to X(92)	Effective capillary pressures
X(93)	Provisional total outflow of displaced fluid
X(94)	Provisional total outflow of displacing fluid
X(95) to X(102)	Provisional inflow of displaced fluid in tubes
X(103) to X(110)	Provisional inflow of displacing fluid in tubes
X(111) to X(118)	Provisional outflow of displaced fluid from tubes
X(119) to X(126)	Provisional outflow of displacing fluid from tubes
IR	No. of rows in network
JR	No. of column in network
GAMA	Interfacial tension
THETA	Contact angle
RAD	Tube radius

COM	Cumulative distribution
GRID	Grid size
TRAP	Value of trapping factor
HYST	Hysteresis in contact angle (=0)
TIME	Time step
ISTAR-IFIN	No. of time steps for each pressure
AV	Displaced fluid content of the network
ICP	No. of pressure steps

FORTRAN SOURCE LIST

SOURCE STATEMENT

```
$IBFTC CALC                                                                    BPP00002
      COMMON/SYMARG/X(50,16 ),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,BPP00033
     1XA     ,EP(  ,  ),HYST,CAT,GAMMA,J,FLO(50,8),GRID                       BPP00040
      COMMON/PRESS/NN,A(50,50),AB(50)                                          BPP00050
      COMMON/SOL/AA(50,50),BB(50),AV(40),WR(40),WO(40),WI(40),DEN(40)          BPP00060
      COMMON/SOLB/CAP(10,10),I,ICHANG,ARAT,TRAP                                BPP00070
      COMMON/CHAN/DIFO,WDIF                                                    BPP00080
      COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFO(50,8),BASE                      BPP00090
      COMMON/SOLC/AOO,CP,JIM,ICP                                               BPP00100
      COMMON/SIM/COM(15),RAD(15),KL,LK                                         BPP00110
C     READ AND PRINT ALL THE RELEVANT INPUT DATA                               BPP00120
      CALL FLUN(99999)                                                         BPP00122
      DO 9  IKJ=1,2                                                            BPP00127
      READ 1  ,IR,JR,GAMMA,THETA,CP,VO,VW                                      BPP00130
      PRINT987                                                                 BPP00132
  987 FORMAT(1H1 )                                                             BPP00134
      PRINT 1 ,IR,JR,GAMMA,THETA,CP,VO,VW                                      BPP00140
      READ 20,KL,LK                                                            BPP00150
      PRINT 30,IR,JR,KL,LK                                                     BPP00160
      READ 40,(COM(I),I=1,LK)                                                  BPP00170
      PRINT 40,(COM(I),I=1,LK)                                                 BPP00180
      READ 40,(RAD(J),J=1,LK)                                                  BPP00190
      PRINT 40,(RAD(J),J=1,LK)                                                 BPP00200
      PRINT 40,VO,VW,CP                                                        BPP00210
      READ 40,GRID                                                             BPP00220
      PRINT 40,GRID                                                            BPP00230
      READ 12,XA,HYST,TRAP                                                     BPP00240
      PRINT 12,XA,HYST,TRAP                                                    BPP00250
      READ 7,TIME                                                              BPP00260
      PRINT 7,TIME                                                             BPP00270
      READ 10,ISTAR,IFIN                                                       BPP00280
      PRINT 10,ISTAR,IFIN                                                      BPP00290
      I=ISTAR-1                                                                BPP00300
      READ 37,WR(I+1),DEN(I+1),STW,STO                                         BPP00310
      IF(ISTAR.EQ.1)I=1                                                        BPP00320
      READ 37,AV(1),WO(1), WO(I),WI(I)                                         BPP00330
      AOO=WO(I)                                                                BPP00340
    7 FORMAT(1X,E15.10)                                                        BPP00350
   10 FORMAT(2I3,6F10.5)                                                       BPP00360
   11 FORMAT(20X,4I4)                                                          BPP00370
   12 FORMAT(8F10.5)                                                           BPP00380
   13 FORMAT(6F10.5)                                                           BPP00390
   14 FORMAT(12F10.5)                                                          BPP00400
   40 FORMAT(1X,8F10.5)                                                        BPP00410
   30 FORMAT(1X,2I8)                                                           BPP00420
   37 FORMAT(4X,8E12.5)                                                        BPP00430
   50 FORMAT(20X,15HOIL SATURATION=,F10.4,17HWATER SATURATION=,F10.4)          BPP00440
   51 FORMAT(20X,7HTHE PT.,I4,25HIS BETWEEN 1AND 4 IN C73  )                   BPP00450
   52 FORMAT(20X,7HTHE PT.,I4,12HHAS 4 IN C73  )                               BPP00460
  100 FORMAT(//// 8(9X,1H ))                                                   BPP00470
  111 FORMAT(30X,21HPRESSURE DISTRIBUTION  )                                   BPP00480
  117 FORMAT(//1X,30X,18HFLUID DISTRIBUTION  )                                 BPP00490
  310 FORMAT(//20X,I4,7F13.5//)                                                BPP00500
  759 FORMAT(20X,*CONTACT ANGLE=* F6.2,*DEGREES*)                              BPP00510
  760 FORMAT(20X,*VISCOSITY RATIO(OIL/WATER)=*,F6.2)                           BPP00520
```

FORTRAN SOURCE LIST CALC

SOURCE STATEMENT

```
751 FORMAT(3HL)                                                          BPP00530
    N=IR*JR                                                              BPP00540
    JIM=N-JR                                                             BPP00550
    THETA IS CONTACT ANGLE AND GAMMA IS INTERFACIAL TENSION              BPP00560
    ARAT=VO/VW                                                           BPP00570
    ARG=THETA*3.2416/180.                                                BPP00580
    GC=1.782*GAMMA*COS(ARG)/68947.31                                     BPP00590
    CAT=0.0                                                              BPP00600
    PRINT 759,THETA                                                      BPP00610
    READ DATA FROM TAPE                                                  BPP00620
    CALL SIMU                                                            BPP00630
    PRINT37,((X(J,K),K=1,8),J=1,N)                                       BPP00640
    PRINT37,((X(J,K),K=57,64),J=1,N)                                     BPP00650
    DO 20 IJ=1,N                                                         BPP00660
    IK=IJ/JR+1                                                           BPP00670
    JK=IJ-JR*(IK-1)                                                      BPP00680
    IF(JK.LE.0)IK=IK-1                                                   BPP00690
    IF(JK.LE.0)JK=JR                                                     BPP00700
    EP(IK,JK)=X(IJ,74)                                                   BPP00710
    CAP(IK,JK)=0.0                                                       BPP00720
    DO 39 IA=1,8                                                         BPP00730
    X(IJ,IA+16)=1.0                                                      BPP00740
    X(IJ,IA+24)=1.0                                                      BPP00750
    X(IJ,IA+136)=THETA                                                   BPP00760
    IF(X(IJ,IA).EQ.0.0)X(IJ,IA+24)=2.0                                   BPP00770
    X(IJ,IA+40)=X(IJ,IA+32)*VO/VW                                        BPP00780
    X(IJ,IA+56)=X(IJ,IA+48)                                              BPP00790
    X(IJ,IA+74)=X(IJ,IA+32)                                              BPP00800
    X(IJ,IA+84)=0.0                                                      BPP00810
    X(IJ,IA+94)=0.0                                                      BPP00820
    X(IJ,IA+102)=0.0                                                     BPP00830
    X(IJ,IA+110)=0.0                                                     BPP00840
    X(IJ,IA+118)=0.0                                                     BPP00850
 39 CONTINUE                                                             BPP00860
    X(IJ,83)=0.0                                                         BPP00870
    X(IJ,84)=0.0                                                         BPP00880
    X(IJ,93)=0.0                                                         BPP00890
    X(IJ,73)=1.0                                                         BPP00900
    X(IJ,94)=0.0                                                         BPP00910
 20 CONTINUE                                                             BPP00920
    PRINT 12,GAMMA                                                       BPP00930
    STW=0.0                                                              BPP00940
    STO=0.0                                                              BPP00950
    AV(1)=0.0                                                            BPP00960
    DO 900 ICP=1,12                                                      BPP00970
    WI(1)=0.0                                                            BPP00980
    DO 900 ICP=1,10                                                      BPP00981
    IF(ICP.GE.3)TIME=0.001                                               BPP00982
    IF(ICP.GE.5)TIME=0.005                                               BPP00983
    IF(ICP.GE.8)TIME=0.01                                                BPP00990
    READ7,CP                                                             BPP01000
    PRINT7, CP                                                           BPP01010
    DO 700 I=ISTAR,IFIN                                                  BPP01020
    IF(ICP.EQ.1)  WO(1)=0.0                                              BPP01030
    IF(ICP.EQ.1)WI(1)=0.0
```

FORTRAN SOURCE LIST CALC

```
      SOURCE STATEMENT
   48 CONTINUE                                                          BPP01040
C     FRAME EXAMINE AND SOLVE THE SYSTEM OF EQUATIONS                  BPP01050
      CALL SOLVE                                                       BPP01060
      IF(ICP.LT.10) GO TO 107                                          BPP01070
  108 PRINT 111                                                        BPP01080
C     PRINT PRESS DISTRIBUTION                                         BPP01090
      DO 107 IB=1,IR                                                   BPP01100
      PRINT 113                                                        BPP01110
      PRINT 14,(EP(IB,JK),JK=1,JR)                                     BPP01120
  107 CONTINUE                                                         BPP01130
      PRINT 117                                                        BPP01140
      AOO=0.0                                                          BPP01150
      AWO=0.0                                                          BPP01160
      SWL=0.0                                                          BPP01170
      IF(I.NE.1)SWL=1.0-AV(I)/AV(1)                                    BPP01180
      AV(I)=0.0                                                        BPP01190
      ILK=0                                                            BPP01200
      SATL=0.0                                                         BPP01210
      SATO=0.0                                                         BPP01220
      DO 300 KRS=1,N                                                   BPP01230
C     CALL POINTS IN PROPER SEQUENCE                                   BPP01240
      IF(KRS.LE.ILK) GO TO 300                                         BPP01250
      DO 305 K=KRS,N                                                   BPP01260
      IK=K/JR+1                                                        BPP01270
      JK=K-JR*(IK-1)                                                   BPP01280
      IF(JK.LE.0)IK=IK-1                                               BPP01290
      IF(JK.LE.0)JK=JR                                                 BPP01300
      IF(JK.EQ.JR)GO TO 320                                            BPP01310
      DPE=EP(IK,JK)-EP(IK,JK+1)+CAP(IK,JK)                             BPP01320
      IF(DPE.GE.0.0)GO TO 320                                          BPP01330
  305 CONTINUE                                                         BPP01340
  320 ILK=K                                                            BPP01350
      MK=ILK-KRS+1                                                     BPP01360
      DO 350 KR=1,MK                                                   BPP01370
      IJ=ILK-KR+1                                                      BPP01380
      J=IJ                                                             BPP01381
      IF(ICP.LT.15)GO TO 2                                             BPP01390
      PRINT 10,IJ                                                      BPP01391
    2 CONTINUE                                                         BPP01400
      IK=IJ/JR+1                                                       BPP01410
      JK=IJ-JR*(IK-1)                                                  BPP01420
      IF(JK.LE.0) IK=IK-1                                              BPP01430
      IF(JK.LE.0)JK=JR                                                 BPP01440
      IJA=IJ                                                           BPP01450
      M=1                                                              BPP01460
      VWI=0.0                                                          BPP01470
      VOI=0.0                                                          BPP01480
      MMK=0                                                            BPP01490
      BASE=0.0                                                         BPP01500
      IF(X(J,73).EQ.4.0) GO TO 291                                     BPP01510
C     COMPUTE FLOW RATES FOR OIL AND WATER INCOMING OUTGOING           BPP01520
      CALL FLOW                                                        BPP01530
      VOI=X(J,83)                                                      BPP01540
      VWI=X(J,84)                                                      BPP01550
      IF(IK.EQ.1)VOI=0.0
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FORTRAN SOURCE LIST CALC

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      SOURCE STATEMENT
      IF(IK.EQ.1)VWI=0.0                                                BPP01560
      IF(IK.EQ.1)GO TO 214                                              BPP01570
C     UPDATE X(73)=LIQUIDS ENTERING THE JUNCTION POINT                  BPP01580
      IF(VOI.EQ.0.0.AND.VWI.EQ.0.0)X(J,73)= 4.0                         BPP01590
      IF(VOI.EQ.0.0.AND.VWI.NE.0.0)X(J,73)=2.0                          BPP01600
      IF(VOI.NE.0.0.AND.VWI.NE.0.0)X(J,73)=3.0                          BPP01610
      IF(VOI.NE.0.0.AND.VWI.EQ.0.0)X(J,73)=1.0                          BPP01620
      VOI=ABS(VOI)                                                      BPP01630
      VWI=ABS(VWI)                                                      BPP01640
      IF(IJ.GT.JIM)GO TO 29                                             BPP01650
C     COMPUTE OUT FLOWING VOLUMES                                       BPP01660
  214 VOO=X(J,93)                                                       BPP01670
      VWO=X(J,94)                                                       BPP01680
      VOO=ABS(VOO)                                                      BPP01690
      VWO=ABS(VWO)                                                      BPP01700
      DELTA=VOI+VWI-VOO-VWO                                             BPP01710
      IF(VOO.LE.0.10E-10)VOO=0.0                                        BPP01720
      IF(VWO.LE.0.10E-10)VWO=0.0                                        BPP01730
      IF(VWI.LE.0.10E-10)VWI=0.0                                        BPP01740
      IF(VOI.LE.0.10E-10)VOI=0.0                                        BPP01750
      IF(ABS(DELTA).LE.0.10E-10) DELTA=0.0                              BPP01760
      DELO=VOI-VOO                                                      BPP01770
      DELOW=VWI-VWO                                                     BPP01780
      DELO=ABS(DELO)                                                    BPP01790
      DELOW=ABS(DELOW)                                                  BPP01800
      IF(DELO.LT.0.1E-10)VOO=VOI                                        BPP01810
      IF(DELOW.LT.0.1E-10) VWO=VWI                                      BPP01820
      IF(ICP.LT.15)GO TO 1                                              BPP01830
  888 PRINT37,VOI,VOO,VWI,VWO,DELTA                                     BPP01840
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=75,82)                        BPP01850
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=65,72)                        BPP01860
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA+94),KA=1,32)                      BPP01870
      IF(DELTA.EQ.0.)PRINT37,(X(J,KA),KA=75,82)                         BPP01880
      IF(DELTA.EQ.0.)PRINT37,(X(J,KA),KA=65,72)                         BPP01890
    1 CONTINUE                                                          BPP01900
C     UPDATE OIL CONTENT OF TUBES                                       BPP01910
      DO 21 K=1,8                                                       BPP01920
      DEN(K)=X(J,K+55)                                                  BPP01930
   21 X(J,K+56)=VOF(J,K)                                                BPP01940
      DO 470 JP=1,8                                                     BPP01950
      ICAN(J,JP)=0                                                      BPP01960
      AWDIF(J,JP)=0.0                                                   BPP01970
      ADIFO(J,JP)=0.0                                                   BPP01980
      IF(X(J,JP+16).EQ.0.0)PRINT 11,IJ,JP                               BPP01990
  470 CONTINUE                                                          BPP02000
      CASE=0.0                                                          BPP02010
      IF(IK.NE.1.AND.VOO.EQ.0.0.AND.VWO.EQ.0.0)X(J,73)=4.0              BPP02020
      IF(IK.EQ.1.AND.VOO.EQ.0.0.AND.VOI.EQ.0.0.AND.VWO.EQ.0.0.AND.VWI.  BPP02030
     1EQ.0.0)X(J,73)=4.0                                                BPP02040
      IF (X(J,73).EQ.4.0) CASE=1.0                                      BPP02050
      IF(X(J,73).EQ.4.0) GO TO 270                                      BPP02060
C     COMPENSATE FOR IMBA ANCE IM INFLOW-OUTFLOW AT A POINT BYPICKING TUBPP02070
C     MONTE CARLO TECHNIQUE                                             BPP02080
      IF(IJ.LE.JR) CASE=1.0                                             BPP02090
      IF(IJ.LE.JR) GO TO 4805                                           BPP02100
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FORTRAN SOURCE LIST CALC

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      SOURCE STATEMENT

      IF(VOI.GE.VOO.AND.VWI.GE.VWO)CASE=1.0                              BPP02
      IF(VOI.GE.VOO.AND.VWI.GE.VWO) GO TO 4805                           BPP02
      IF((VOI+VWI).LE.0.0) GO TO 4805                                    BPP02
      WDIF=VWI-VWO-(DELTA*VWI)/(VOI+VWI)                                 BPP02
      DIFO=VOI-VOO-(DELTA*VOI)/(VOI+VWI)                                 BPP02
      IF(WDIF.LE.0.1E-10)WDIF=0.0                                        BPP02
      IF(DIFO.LE.0.1E-10)DIFO=0.0                                        BPP02
      IF(DIFO.LE.0.0.AND.WDIF.LE.0.0)GO TO 4805                          BPP02
      CALL CHANGE                                                        BPP02
      IF(DIFO.NE.0.0.OR.WDIF.NE.0.0)PRINT37,(X(J,KA+74),KA=1,8)          BPP02
C     BASE.EQ.1.0 MEANS UPSTREAM DATA HAS TO BE CORRECTED DUE TO FLOW CHBPP02
 4805 DO 1005 K=1,8                                                      BPP02
      X(J,K+56)=DEN(K)                                                   BPP02
      X(J,K+16)=FLO(J,K)                                                 BPP02
      IF(X(J,K+24).GE.1.5)GO TO 1005                                     BPP02
      IF(X(J,K+64).LE.0.0)GO TO 1005                                     BPP02
      X(J,K+110)=X(J,K+94)+X(J,K+56)-VOF(J,K)                            BPP02
      X(J,K+118)=X(J,K+102)+VOF(J,K)-X(J,K+56)                           BPP02
      X(J,K+56)=VOF(J,K)                                                 BPP02
 1005 CONTINUE                                                           BPP02
  270 CAT=1.0                                                            BPP02
      CALL COND(1)                                                       BPP02
      CAT=0.0                                                            BPP02
      IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291                             BPP02
      IF(BASE.EQ.1.0) GO TO 479                                          BPP02
      ICAN(J,M)=0                                                        BPP02
      GO TO 483                                                          BPP02
  479 DO 481 ICA=6,8                                                     BPP02
      IF(BASE.EQ.1.0)PRINT 11,IJ,ICAN(J,1),ICAN(J,7),ICAN(J,8)           BPP02
      IF(BASE.EQ.1.0)BASE=2.0                                            BPP02
      M=ICA                                                              BPP02
      IF(ICA.EQ.6)M=1                                                    BPP02
      MMK=ICAN(J,M)                                                      BPP02
      ICAN(J,M)=0                                                        BPP02
      IF(MMK.EQ.0) GO TO 482                                             BPP02
      WDIF=AWDIF(J,M)                                                    BPP02
      DIFO=ADIFO(J,M)                                                    BPP02
      IF(X(J,M+64).GT.0.0)CASE=2.0                                       BPP02
      IF(CASE.LT.2.0)J=MMK                                               BPP02
      IF(WDIF.LE.0.0.AND.DIFO.LE.0.0) GO TO 482                          BPP02
      DO 478 K=1,8                                                       BPP02
      FLO(J,K)=X(J,K+16)                                                 BPP02
      VOF(J,K)=X(J,K+56)                                                 BPP02
      AP(J,K)=0.0                                                        BPP02
      IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)                              BPP02
  478 CONTINUE                                                           BPP02
  430 IF(WDIF.LE.0.1E-10)WDIF=0.0                                        BPP02
      IF(DIFO.LE.0.1E-10)DIFO=0.0                                        BPP02
      IF(DIFO.LE.0.0.AND.WDIF.LE.0.0) GO TO 485                          BPP02
      CALL CHANGE                                                        BPP02
C     ENTER CHANGES IN VOL OUTFLOW/INFLOW,AND FLUID CONTENT              BPP02
  435 CONTINUE                                                           BPP02
  486 DO 105 K=1,8                                                       BPP02
      X(J,K+56)=DEN(K)                                                   BPP02
      X(J,K+16)=FLO(J,K)                                                 BPP02
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FORTRAN SOURCE LIST CALC

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N       SOURCE STATEMENT

1       IF(X(J,K+24).GE.1.5)GO TO 105                                   BPP02530
4       IF(X(J,K+64).LE.0.0)GO TO 105                                   BPP02540
7       X(J,K+110)=X(J,K+94)+X(J,K+56)-VOF(J,K)                         BPP02550
0       X(J,K+118)=X(J,K+102)+VOF(J,K)-X(J,K+56)                        BPP02560
1       X(J,K+56)=VOF(J,K)                                              BPP02570
2   105 CONTINUE                                                        BPP02580
4       CAT=1.0                                                         BPP02590
5       CALL COND(1)                                                    BPP02600
6       CAT=0.0                                                         BPP02610
7       IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291                          BPP02620
2       IF(BASE.EQ.1.0) GO TO 479                                       BPP02630
5       ICAN(J,M)=0                                                     BPP02640
6   482 CONTINUE                                                        BPP02650
7   481 CONTINUE                                                        BPP02660
1   483 BASE=0.0                                                        BPP02670
2       MMK=0                                                           BPP02680
3       J=IJA                                                           BPP02690
4   291 IB=IJ+JR                                                        BPP02700
5       DO 330 K=6,9                                                    BPP02710
6       IA=K                                                            BPP02720
7       IF(K.EQ.9) IA=1                                                 BPP02730
2       AV(I)=AV(I)+X(J,IA+56)                                          BPP02740
3       IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT36,J,IA   BPP02741
6       IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT37,X(J,IA+48BPP02742
       1),X(J,IA+56)                                                    BPP02743
1   330 CONTINUE                                                        BPP02750
3       IF(I.EQ.1.AND.ICP.EQ.1)VOLPOR=AV(1)                             BPP02760
C       COMPUTE TOTAL OUTFLOW OF FLUIDS FROM THE SAMPLE                 BPP02770
6       IF(VOI.LE.0.10E-10)VOI=0.0                                      BPP02780
1       IF(VWI.LE.0.10E-10)VWI=0.0                                      BPP02790
4       IF(IB.LE.N) GO TO 292                                           BPP02800
7       IF(ICP.LT.15)GO TO 3                                            BPP02801
2       PRINT 37,VOI,VWI                                                BPP02810
3     3 CONTINUE                                                        BPP02811
4       AOO=AOO+VOI                                                     BPP02820
5       AWO=AWO+VWI                                                     BPP02830
6       DO 290 IA=7,9                                                   BPP02840
7       K=IA                                                            BPP02850
9       IF(K.EQ.9) K=1                                                  BPP02860
3       SATL=SATL+X(J,K+56)                                             BPP02870
4       SATO=SATO+X(J,K+48)                                             BPP02880
5   290 CONTINUE                                                        BPP02890
7   292 CONTINUE                                                        BPP02900
C       PRINT FLOW DISTRIBUTION                                         BPP02910
0       IF(ICP.LT.15)GO TO 4                                            BPP02911
3       PRINT37,(X(J,KA),KA=57,64)                                      BPP02913
9   777 PRINT12,(X(J,K),K=17,32)                                        BPP02920
5       IF(X(J,73).EQ.4.0) PRINT52,IJ                                   BPP02930
0     4 CONTINUE                                                        BPP02931
1       IF(I.EQ.1.AND.ICP.EQ.1)GO TO 2222                               BPP02940
4       GO TO 79                                                        BPP02950
5  2222 CONTINUE                                                        BPP02960
6       IF(IK.NE.1)GO TO 213                                            BPP02970
1       X(J,73)=2.0                                                     BPP02980
2       DO 212 K=3,5                                                    BPP02990
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FORTRAN SOURCE LIST CALC 12/04/

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N       SOURCE STATEMENT

3           IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.0                          BPP03000
6       212 CONTINUE                                                    BPP03010
0       213 IF(IK.NE.2) GO TO 79                                        BPP03020
3           DO 216 IA=7,9                                               BPP03030
4           K=IA                                                        BPP03040
5           IF(K.EQ.9) K=1                                              BPP03050
0           IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.5                          BPP03060
3       216 CONTINUE                                                    BPP03070
5        79 CONTINUE                                                    BPP03080
6           X(J,83)=0.0                                                 BPP03090
7           X(J,84)=0.0                                                 BPP03100
0           X(J,93)=0.0                                                 BPP03110
1           X(J,94)=0.0                                                 BPP03120
2           VOI=0.0                                                     BPP03130
3           VWI=0.0                                                     BPP03140
4       296 CONTINUE                                                    BPP03150
5       350 CONTINUE                                                    BPP03160
7       300 CONTINUE                                                    BPP03170
1           PRINT37,AV(I)                                               BPP03180
2           SO=AV(I)/VOLPOR                                             BPP03190
3           SW=1.0-SO                                                   BPP03200
4           PRINT 50,SO,SW                                              BPP03210
5       690 CONTINUE                                                    BPP03220
6           WI(I)=AWO                                                   BPP03230
7           WI(1)=WO(1)*ARAT                                            BPP03240
0           CUML=(STO+STW)/AV(1)                                        BPP03250
1           WO(I)=AOO                                                   BPP03260
2           STW=STW+WI(I)                                               BPP03270
3           STO=STO+WO(I)                                               BPP03280
4           PRINT 37, WO(1),WO(I),STO,STW,WI(I)                         BPP03290
5           W=WO(1)*0.01                                                BPP03300
6           IF(I.GT.2.AND.AOO.LE.W) GO TO 800                           BPP03310
1       700 CONTINUE                                                    BPP03320
3       800 CONTINUE                                                    BPP03330
4       900 CONTINUE                                                    BPP03340
  C         CALCULATE AND PRINT POROSITY AND PERMEABILITY               BPP03350
0           AJR=JR                                                      BPP03360
1           AIR=IR                                                      BPP03370
2           POR=AV(1)/((AJR-1.)*(AIR-1.)*GRID**3)                       BPP03380
3           PERM=WI(1)*VW*(AIR-1.)/(TIME*GRID*(AJR-1.)*CP)              BPP03390
4           PRINT 12, POR,PERM                                          BPP03400
5           STOP                                                        BPP03410
6           END                                                         BPP03420
                                IBMAP ASSEMBLY CALC                     12/04/
ROR MESSAGES

T 307       ERROR 1311  ISN-221   DO VARIABLE REDEFINED IN ITS OWN RANGE.

VERITY WAS 0.
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FORTRAN SOURCE LIST UB 1

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N       SOURCE STATEMENT

0       CALL PDIF                                                          BPP03980
  C     AVOID INFLOW FROM OUTLET END OR FROM INLET END .TRAP APPROPRIATE TBPP0399
  C     UBES                                                               BPP04
1       K=IJ                                                               BPP04020
2       DO 76 KL=2,5                                                       BPP0402
3       IF(K.GT.JIM) GO TO 76                                              BPP04
6       COL=0.0                                                            BPP04
7       IJK=IJ                                                             BPP04050
0       IF(X(IJK,KL+24).GE. 1.5) GO TO 76                                  BPP04
3       AS=0.0                                                             BPP04
4       IF(K.GT.NN.AND.K.LE.JIM) AS=1.0                                    BPP04
7       IF(AS.EQ.1.0.AND.X(IJK,KL+64).LT.0.0) AS=2. 0                      BPP04090
2       IF(AS.EQ.2.0.AND.KL.GE.3.AND.KL.LE.5)COL=0.5                       BPP04
5       IF(K.LE.JR.AND.X(IJK,KL+64).LT.0.0) COL=0.5                        BPP04
0       IF(X(IJK,KL+16).LE.2.0) GO TO 55                                   BPP04120
3       IF(X(IJK,KL+16).GT.4.0)GO TO 55                                    BPP04
6       IF(K.LE.JR) GO TO 55                                               BPP04
1       DP=0.0                                                             BPP04
2       DP=X(IJK,KL+84)                                                    BPP04160
3       DP=DP*(1.+TRAP)                                                    BPP04161
4       ADP=X(IJK,KL+64)-X(IJK,KL+84)                                      BPP04
5       IF(DP.LE.0.0.AND.ADP.LE.0.0) GO TO 55                              BPP04
0       IF(ADP.GE.0.0.AND.DP.GE.0.0) GO TO 55                              BPP04190
3       DP=ABS(DP)                                                         BPP04
4       ADP=ABS(ADP)                                                       BPP04
5       IF(ADP.LT.DP) COL=0.5                                              BPP04220
0    55 IF(COL.EQ.0.5) X(IJK,KL+24)=1.5                                    BPP04230
3       IF(COL.EQ.0.5) CO=0.5                                              BPP04
6    76 CONTINUE                                                           BPP04
0       IF(CO.EQ.0.0) GO TO 77                                             BPP04270
3       CAT=0.0                                                            BPP04280
4       COUNT=COUNT+1                                                      BPP04
5       J=IJ                                                               BPP04310
6       CALL COND(1)                                                       BPP04320
7    77 CONTINUE                                                           BPP04330
0    87 CONTINUE                                                           BPP04
1       DO 82 IL=1,8                                                       BPP04
2       IF(X(IJ ,73).EQ.4.0) GO TO 82                                      BPP04360
5       IF(X(IJ,IL+24).GE.1.5) GO TO 82                                    BPP04
0       CPA=X(IJ,IL+84)                                                    BPP04
1       CPT=CPT+X(IJ,IL+74)*CPA                                            BPP04
2       VS=VS+X(IJ,IL+74)                                                  BPP04
3       IF(IL.EQ.2) CAP(IK,JK)=CPA                                         BPP04
6    82 CONTINUE                                                           BPP04420
0       IF(VS.EQ.0.0) GO TO 85                                             BPP04
3       IF(IJ.LT.IS.OR.IJ.GT.IT) GO TO 85                                  BPP04440
5       VA=0.0                                                             BPP04
7       DO 70 K=1,8                                                        BPP04
0       X(IJ,K+94)=0.0                                                     BPP04473
1       X(IJ,K+102)=0.0                                                    BPP04480
2       X(IJ,K+110)=0.0                                                    BPP0449
3       X(IJ,K+118)=0.0                                                    BPP
4       IA=IK                                                              BPP
5       JA=JK                                                              BPP
6       IF(K.EQ.1) IA=IK-1                                                 BPP
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FORTRAN SOURCE LIST UB 1

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N       SOURCE STATEMENT

1       IF(K.LE.3) JA=JK+1                                              BPP04540
4       IF(K.GE.5.AND.K.LE.7) JA=JK-1                                   BPP04550
7       IF(K.GE.3.AND.K.LE.5)IA=IK+1                                    BPP04560
2       IF(K.GE.7) IA=IK-1                                              BPP04570
5       IJC=(IA-1)*JR+JA                                                BPP04580
6       AA(IJ,IJC)=-X(IJ,K+74)                                          BPP04590
7       IF(IJC.LE.JR) VA=VA+AA(IJ,IJC)*CP                               BPP04600
2    70 CONTINUE                                                        BPP04610
4       BB(IJ)=-VA-CPT                                                  BPP04620
5    85 AA(IJ,IJ)=VS                                                    BPP04630
6    86 CONTINUE                                                        BPP04640
0       IF(IC.NE.1.AND.COUNT.EQ.0) GO TO 78                             BPP04650
3       DO 66 IN=1,NN                                                   BPP04660
4       INR=IN+JR                                                       BPP04670
5       AB(IN)=BB(INR)                                                  BPP04680
6       DO 66 JN=1,NN                                                   BPP04690
7       JNR=JN+JR                                                       BPP04700
0       A(IN,JN)=AA(INR,JNR)                                            BPP04710
1    66 CONTINUE                                                        BPP04720
4       CALL PRSOL(1)                                                   BPP04730
5       CALL PRSOL(2)                                                   BPP04740
6       DO 75 K=1,N                                                     BPP04750
7       BB(K)=CP                                                        BPP04760
0       IF(K.GT.JIM) BB(K)=0.                                           BPP04770
3       IF(K.LE.JR.OR.K.GT.JIM) GO TO 73                                BPP04780
6       KK=K-JR                                                         BPP04790
7       BB(K)=AB(KK)                                                    BPP04800
0    73 IK=K/JR+1                                                       BPP04810
1       JK=K-JR*(IK-1)                                                  BPP04820
2       IF(JK.EQ.0) IK=IK-1                                             BPP04830
5       IF(JK.EQ.0) JK=JR                                               BPP04840
0       EP(IK,JK)=BB(K)                                                 BPP04850
1    75 CONTINUE                                                        BPP04860
3    78 CONTINUE                                                        BPP04870
4       PRINT 10,COUNT                                                  BPP04880
5       IF(COUNT.NE.0) GO TO 80                                         BPP04890
0       IF(IC.EQ.1) GO TO 80                                            BPP04900
3       RETURN                                                          BPP04910
4       END                                                             BPP04920
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IBMAP ASSEMBLY UB 1

ESSAGES FOR ABOVE ASSEMBLY

FORTRAN SOURCE LIST

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N        SOURCE STATEMENT

  $IBFTCSUB C                                                          BPP04930
        SUBROUTINE PRSOL(KKK)                                          BPP04940
        COMMON/PRESS/NN,A(50,50),AB(50)                                BPP04950
        GO TO (1000,2000),KKK                                          BPP04960
  C     REDUCE MATRIX BY GAUSS ELIMINATION PROCEDURE                   BPP04970
   1000 N=NN+1                                                         BPP04980
        DO 230 I=1,NN                                                  BPP04990
        A(I,N)=-AB(I)                                                  BPP05000
    230 CONTINUE                                                       BPP05010
        DO 282 L=1,NN                                                  BPP05020
        M=L+1                                                          BPP05030
        IF(M.GT.NN) GO TO 282                                          BPP05040
        DO 281 I=M,NN                                                  BPP05050
        IF(A(L,L).EQ.0.0) GO TO 281                                    BPP05060
        C=A(I,L)/A(L,L)                                                BPP05070
        IF(C.EQ.0.0) GO TO 281                                         BPP05080
        DO 280 J=1,N                                                   BPP05090
        IF(A(L,J).EQ.0.0) GO TO 280                                    BPP05100
        Z=C*A(L,J)                                                     BPP05110
        A(I,J)=A(I,J)-Z                                                BPP05120
    280 CONTINUE                                                       BPP05130
    281 CONTINUE                                                       BPP05140
    282 CONTINUE                                                       BPP05150
        DO 340 L=1,NN                                                  BPP05160
        I=N-L                                                          BPP05170
        C=A(I,I)                                                       BPP05180
        DO 320 J=1,N                                                   BPP05190
        IF(C.EQ.0.0) GO TO 320                                         BPP05200
        IF(A(I,J).EQ.0.0) GO TO 320                                    BPP05210
        A(I,J)=A(I,J)/C                                                BPP05220
    320 CONTINUE                                                       BPP05230
        BA=A(I,N)                                                      BPP05240
        IA=I-1                                                         BPP05250
        IF(IA.EQ.0) GO TO 340                                          BPP05260
        IF(BA.EQ.0.0) GO TO 340                                        BPP05270
        DO 330 IB=1,IA                                                 BPP05280
        A(IB,N)=A(IB,N)-BA*A(IB,I)                                     BPP05290
    330 A(IB,I)=0.0                                                    BPP05300
    340 CONTINUE                                                       BPP05310
        GO TO 500                                                      BPP05320
   2000 DO 450 I=1,NN                                                  BPP05330
    450 AB(I)=-A(I,N)                                                  BPP05340
    500 RETURN                                                         BPP05350
        END                                                            BPP05360

                        IBMAP ASSEMBLY UB 2                                12/04/

ESSAGES FOR ABOVE ASSEMBLY
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FORTRAN SOURCE LIST

```
      SOURCE STATEMENT

$IBFTCSUB 3                                                                    BPP05570
      SUBROUTINE FLOW                                                          BPP05580
      COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,BPP05590
     1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID                        BPP05600
C     FLOW CAPICITY OF TUBES                                                   BPP05610
      ARAT=VO/VW                                                               BPP05620
      N=IR*JR                                                                  BPP05630
      IB=N-2*JR                                                                BPP05640
      X(J,93)=0.                                                               BPP05650
      X(J,94)=0.0                                                              BPP05660
      DO 200 K=1,8                                                             BPP05670
      VOF(J,K)=X(J,K+56)                                                       BPP05680
      AP(J,K)=0.                                                               BPP05690
      IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)                                    BPP05700
      X(J,K+94)=0.0                                                            BPP05710
      X(J,K+102)=0.0                                                           BPP05720
      X(J,K+110)=0.0                                                           BPP05730
      X(J,K+118)=0.0                                                           BPP05740
      IF(X(J,73).EQ.4.0) GO TO 200                                             BPP05750
C     CASE 2.0 MEANS BACK FLOW                                                 BPP05760
      CASE=0.0                                                                 BPP05770
      FLO(J,K)=X(J,K+16)                                                       BPP05780
      IF(K.GE.3.AND.K.LE.5)CASE=1.0                                            BPP05790
      IF(CASE.EQ.1.0.AND.AP(J,K).EQ.0.0) CASE=2.0                              BPP05800
      IF(CASE.EQ.2.0)AP(J,K)=X(J,K+64)                                         BPP05810
      IF(X(J,K+24).GE.2.0)GO TO 200                                            BPP05820
      VA=AP(J,K)*X(J,K+74)                                                     BPP05830
      VA=VA*TIME                                                               BPP05840
      VA=ABS(VA)                                                               BPP05850
      IF(VA.EQ.0.0)GO TO 200                                                   BPP05860
      IF(CASE.EQ.2.0) GO TO 5                                                  BPP05870
      GO TO 7                                                                  BPP05880
    5 IF(X(J,K+16).EQ.4.2) FLO(J,K)=4.2                                        BPP05890
      IF(X(J,K+16).EQ.4.1) FLO(J,K)=4.1                                        BPP05900
      IF(X(J,K+16).EQ.3.0)FLO(J,K)=3.5                                         BPP05910
      IF(X(J,K+16).EQ.3.5)FLO(J,K)=3.0                                         BPP05920
    7 IF(FLO(J,K).LE.2.0) GO TO 10                                             BPP05930
      IF(FLO(J,K).LT.4.0.AND.FLO(J,K).GE.3.0)GO TO 20                          BPP05940
      IF(FLO(J,K).GE.4.0) GO TO 30                                             BPP05950
   10 IF(FLO(J,K).EQ.1.0) X(J,K+94)=VA                                         BPP05960
      IF(FLO(J,K).EQ.2.0) X(J,K+102)=VA                                        BPP05970
      GO TO 90                                                                 BPP05980
   20 IF(FLO(J,K).EQ.3.5) X(J,K+94)=VA                                         BPP05990
      IF(FLO(J,K).EQ.3.0) X(J,K+102)=VA                                        BPP06000
      GO TO 80                                                                 BPP06010
   30 IF(FLO(J,K).EQ.4.5) GO TO 40                                             BPP06020
      IF(FLO(J,K).EQ.4.1) X(J,K+94)=VA                                         BPP06030
      IF(FLO(J,K).EQ.4.2) X(J,K+102)=VA                                        BPP06040
      SO=X(J,K+56)/X(J,K+48)                                                   BPP06050
      SW=1.-SO                                                                 BPP06060
      AKRW=X(J,K+40)*(2.*SW/ARAT+SW*SW*(1.-2.0/ARAT))                          BPP06070
      AKRN=X(J,K+32)*SO*SO                                                     BPP06080
      AAK=AKRW/VW+AKRN/VO                                                      BPP06090
      AKRW=AKRW*X(J,K+74)/AAK/VW                                               BPP06100
      AKRN=AKRN*X(J,K+74)/AAK/VO                                               BPP06110
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SOURCE STATEMENT

      X(J,K+94)=ABS(AKRN*AP(J,K)*TIME )                                  BPP05830
      X(J,K+102)=ABS(AKRW*AP(J,K)*TIME )                                 BPP05839
      GO TO 80                                                           BPP05840
   40 SO=VOF(J,K)/X(J,K+48)                                              BPP05850
      SW=1.0-SO                                                          BPP05860
      VWET=VW                                                            BPP05870
      VNW=VO                                                             BPP05880
      SWET=SW                                                            BPP05890
      SNW=SO                                                             BPP05900
      IF(GC.LT.0.0)SWET=SO                                               BPP05910
      IF(GC.LT.0.0)SNW=SW                                                BPP05920
      IF(GC.LT.0.0) VNW=VW                                               BPP05930
      IF(GC.LT.0.0) VWET=VO                                              BPP05940
      RWET=SWET*SWET                                                     BPP05950
      RNW=2.0*VNW*SNW+SNW*SNW*(1.0-2.0*VNW/VWET)                         BPP05960
      TOT= RWET/VWET+RNW/VNW                                             BPP05970
      RAW=RWET/VWET/TOT                                                  BPP05980
      RAN=RNW/VNW/TOT                                                    BPP05990
      IF(SW.EQ.SWET) RW=RAW                                              BPP06000
      IF(SW.EQ.SWET)  RO=RAN                                             BPP06010
      IF(SW.EQ.SNW)RW=RAN                                                BPP06020
      IF(SW.EQ.SNW) RO=RAW                                               BPP06030
      X(J,K+94)=RO*VA                                                    BPP06040
      X(J,K+102)=RW*VA                                                   BPP06050
   80 VOMAX=X(J,K+48)                                                    BPP06070
      VOMIN=0.0                                                          BPP06080
      IF(GC.GT.0.0) VOMAX=0.96*X(J,K+48)                                 BPP06090
      IF(GC.LT.0.0)VOMIN=0.04*X(J,K+48)                                  BPP06100
      IF(VOMAX.LT.VOF(J,K))VOMAX=X(J,K+48)                               BPP06110
      IF(VOMIN.GT.VOF(J,K))VOMIN=0.0                                     BPP06120
      VWMAX=X(J,K+48)-VOMIN                                              BPP06130
      VWMIN=X(J,K+48)-VOMAX                                              BPP06140
      IF(FLO(J,K).GT.4.0)GO TO 83                                        BPP06141
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.3.0) GO TO 85                    BPP06150
      V=VA+VOF(J,K)                                                      BPP06160
      IF(V.GT.VOMAX) GO TO 82                                            BPP06170
      VOF(J,K)=VOF(J,K)+VA                                               BPP06180
      X(J,K+110)=0.0                                                     BPP06190
      X(J,K+118)=VA                                                      BPP06200
      IF(GC.GT.0.0)FLO(J,K)=4.5                                          BPP06201
      GO TO 100                                                          BPP06210
   82 CONTINUE                                                           BPP06220
      X(J,K+110)=V-VOMAX                                                 BPP06230
      X(J,K+118)=VOMAX-VOF(J,K)                                          BPP06240
      VOF(J,K)=VOMAX                                                     BPP06241
      FLO(J,K)=1.0                                                       BPP06250
      GO TO 100                                                          BPP06260
   85 V=VA+X(J,K+48)-VOF(J,K)                                            BPP06270
      IF(V.GT.VWMAX) GO TO 86                                            BPP06280
      VOF(J,K)=VOF(J,K)-VA                                               BPP06290
      X(J,K+110)=VA                                                      BPP06300
      X(J,K+118)=0.0                                                     BPP06310
      GO TO 100                                                          BPP06320
   86 CONTINUE                                                           BPP06330
      X(J,K+110)=VOF(J,K)-VOMIN                                          BPP06340
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FORTRAN SOURCE LIST UB 3

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N       SOURCE STATEMENT

1       X(J,K+118)=VA-X(J,K+110)                                        BPP06550
2       VOF(J,K)=VOMIN                                                  BPP06560
3       FLO(J,K)=2.0                                                    BPP06570
4       GO TO 100                                                       BPP06580
5    85 V=VOF(J,K)-VOMIN                                                BPP06590
6       IF(V.LT.X(J,K+94))GO TO 84                                      BPP06600
7       VOF(J,K)=VOF(J,K)-X(J,K+94)                                     BPP06610
2       GO TO 90                                                        BPP06620
3    84 X(J,K+94)=VOF(J,K)-VOMIN                                        BPP06630
4       X(J,K+102)=VA-X(J,K+94)                                         BPP06640
5       VOF(J,K)=VOMIN                                                  BPP06650
6       FLO(J,K)=2.0                                                    BPP06660
7    90 X(J,K+110)=X(J,K+94)                                            BPP06670
0       X(J,K+118)=X(J,K+102)                                           BPP06680
1   100 IF(CASE.EQ.2.0) GO TO 150                                       BPP06690
4       X(J,93)=X(J,93)+X(J,K+94)                                       BPP06700
5       X(J,94)=X(J,94)+X(J,K+102)                                      BPP06710
6       GO TO 200                                                       BPP06720
7   150 CONTINUE                                                        BPP06730
0       X(J,K+94)=X(J,K+110)                                            BPP06740
1       X(J,K+102)=X(J,K+118)                                           BPP06750
2       X(J,83)=X(J,83)+X(J,K+110)                                      BPP06760
3       X(J,84)=X(J,84)+X(J,K+118)                                      BPP06770
4       IF(IJ.LE.JR) X(J,K+24)=2.0                                      BPP06780
7       IF(IJ.GT.IB) X(J,K+24)=2.0                                      BPP06790
2       IF(X(J,K+ 24).EQ.2.0) X(J,K+74)=0.0                             BPP06800
5       IF(X(J,K+24).EQ.2.0) X(J,K+84)=0.0                              BPP06810
0       IF(X(J,K+24).EQ.2.0) X(J,K+24)=1.5                              BPP06820
3       X(J,K+110)=0.0                                                  BPP06830
4       X(J,K+118)=0.0                                                  BPP06840
5   200 CONTINUE                                                        BPP06850
7       RETURN                                                          BPP06860
0       END                                                             BPP06870
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IBMAP ASSEMBLY UB 3

ESSAGES FOR ABOVE ASSEMBLY

FORTRAN SOURCE LIST

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      SOURCE STATEMENT

$IBFTCSUB 4                                                                  BPP0656
      SUBROUTINE COND(KKK)                                                   BPP0657
      COMMON/SYMARG/X(50,16 ),AP(50,8),GC,VD,VW,TIME,VOF(50,8),IJ,IR,JR,BPP0658
     1XA     ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID                     BPP0659
      COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFO(50,8),BASE                    BPP0660
      GO TO (270,79),KKK                                                     BPP0661
C     ENTER CHANGES IN OTHER CONNECTED NODE POINTS                           BPP0662
  270 CONTINUE                                                               BPP0663
   11 FORMAT(20X,4I5)                                                        BPP0664
   13 FORMAT(10X,8F13.5)                                                     BPP0665
      N=IR*JR                                                                BPP0666
      JIM=N-JR                                                               BPP0667
      VS=0.0                                                                 BPP0668
      IF(BASE.EQ.2.0)VS=1.0                                                  BPP0669
      DO 280 M=1,8                                                           BPP0670
      IF(X(J,M+24).EQ.1.5) GO TO 300                                         BPP0671
      IF(JIM.LT.IJ) GO TO 273                                                BPP0673
      IF(X(J,M+64).LE.0.0) GO TO 280                                         BPP0674
  273 IF(X(J,M+24).GE.2.0) GO TO 280                                         BPP0675
  300 CONTINUE                                                               BPP0676
      IF(X(J,M).EQ.0.0) GO TO 280                                            BPP0677
      NX=M+4                                                                 BPP0678
      IF(NX.GT.8) NX=M-4                                                     BPP0679
      MMK=IJ+JR-M+4                                                          BPP0680
      IF(M.EQ.1) MMK=IJ-JR+1                                                 BPP0681
      IF(M.EQ.2)MMK=IJ+1                                                     BPP0682
      IF(M.EQ.6)MMK=IJ-1                                                     BPP0683
      IF(M.EQ.7) MMK=IJ-JR-1                                                 BPP0684
      IF(M.EQ.8) MMK=IJ-JR                                                   BPP0685
      IF(MMK.GT.N) GO TO 280                                                 BPP0686
      IF(MMK.LE.0) GO TO 280                                                 BPP0687
      X(MMK,NX+56)=X(J,M+56)                                                 BPP0688
      X(MMK,NX+16)=X(J,M+16)                                                 BPP0689
      IF(X(J,M+16).EQ.4.1) X(MMK,NX+16)=4.1                                  BPP0690
      IF(X(J,M+16).EQ.4.2) X(MMK,NX+16)=4.2                                  BPP0691
      IF(X(J,M+16).EQ.3.5) X(MMK,NX+16) =3.0                                 BPP0692
      IF(X(J,M+16).EQ.3.0) X(MMK,NX+16) =3.5                                 BPP0693
      IF(X(J,73).EQ.4.0) X(MMK,NX+24)=2.0                                    BPP0694
      IF(X(J,73).EQ.4.0) X(J,M+24)=2.0                                       BPP0695
      IF(X(MMK,73).EQ.4.0) GO TO 275                                         BPP0696
      IF(X(J,M+24).EQ.1.5) X(MMK,NX+24)=2.0                                  BPP0697
      IF(X(J,M+24).EQ.1.5) X(J,M+24) =2.0                                    BPP0698
      IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+74)=0.0                               BPP0699
      IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+84)=0.0                               BPP0700
      IF(X(MMK,NX+24).EQ.2.0) X(J,M+74)=0.0                                  BPP0701
      IF(X(MMK,NX+24).EQ.2.0) X(J,M+84)=0.0                                  BPP0702
      IF(X(MMK,NX+24).EQ.2.0) GO TO 275                                      BPP0703
  274 IF(CAT.NE.1.0) GO TO 275                                               BPP0704
      IF(X(J,M+24).EQ.1.5)X(MMK,NX+24)=2.0                                   BPP0705
      IF(X(J,M+24).EQ.1.5)X(J,M+24)=2.0                                      BPP0706
      IF(VS.NE.0.0) GO TO 275                                                BPP0707
      IF(M.EQ.1.OR.M.GE.7) GO TO 272                                         BPP0708
      X(MMK,83)=X(MMK,83)+X(J,M+110)                                         BPP0709
      X(MMK,84)=X(MMK,84)+X(J,M+118)                                         BPP0710
      GO TO 275                                                              BPP0711
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FORTRAN SOURCE LIST UB 4

SOURCE STATEMENT

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  272 CONTINUE                                                                  BPP07120
      IF(X(J,M+16).EQ.3.5.OR.X(J,M+16).EQ.3.5) GO TO 275                        BPP07130
      IF(X(J,M+110).NE.X(MMK,NX+94)) ADIFO(J,M)=X(J,M+110)-X(MMK,NX+94)         BPP07140
      IF(X(J,M+118).NE.X(MMK,NX+102)) AWDIF(J,M)=X(J,M+118)-X(MMK,NX+          BPP07150
     1102)                                                                      BPP07160
      IF(ADIFO(J,M).NE.0.0.AND.AWDIF(J,M).NE.0.0) BASE=1.0                      BPP07170
      X(MMK,NX+94)=X(J,M+110)                                                   BPP07180
      X(MMK,NX+102)=X(J,M+118)                                                  BPP07190
      IF(BASE.EQ.1.0) ICAN(J,M)=MMK                                             BPP07200
      IF(BASE.EQ.1.0)PRINT 13,X(J,M+74),X(J,M+64),X(J,M+16),X(MMK,NX+74),BPP07210
     1X(MMK,NX+64),X(MMK,NX+16)                                                 BPP07220
      IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0)PRINT 11,IJ,MMK,ICAN(J,M)             BPP07230
      IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0) PRINT 13,X(J,M+110),X(J,M+118BPP07240
     1),X(J,M+94),X(J,M+102)                                                    BPP07250
  275 CONTINUE                                                                  BPP07260
  280 CONTINUE                                                                  BPP07270
      GO TO 500                                                                 BPP07280
C     FILL PROPER CONDUCTIVITIES                                              BPP07290
   79 DO 78 K=1,8                                                             BPP07300
      BASE=0.0                                                                  BPP07310
      IF(X(J,K).EQ.0.0) GO TO 78                                                BPP07320
      IF(CAT.EQ.1.0)X(J,K+24)=1.0                                               BPP07330
      IF(X(J,73).EQ.4.0) X(J,73)=3.0                                            BPP07340
      SO=X(J,K+56)/X(J,K+48)                                                    BPP07350
      SW=1.0-SO                                                                 BPP07360
      IF(X(J,K+16).EQ.1.0) X(J,K+74)=X(J,K+32)                                  BPP07370
      IF(X(J,K+16).EQ.2.0) X(J,K+74)=X(J,K+40)                                  BPP07380
      IF(X(J,K+16).EQ.1.0.OR.X(J,K+16).EQ.2.0) GO TO 830                        BPP07390
      IF(X(J,K+16).NE.4.5) GO TO 821                                            BPP07400
      VL=VO                                                                     BPP07410
      IF(VW.GT.VL) VL=VW                                                        BPP07420
      X(J,K+74)=X(J,K+32)*VO/(VO*SO+VW*SW+6.0*VL*X(J,K))                        BPP07430
      GO TO 830                                                                 BPP07440
  821 IF(X(J,K+16).EQ.3.0.OR.X(J,K+16).EQ.3.5) GO TO 822                        BPP07450
      GO TO 823                                                                 BPP07460
  822 X(J,K+74)=X(J,K+32) *VO/(VO*SO+VW*SW)                                     BPP07470
      GO TO 830                                                                 BPP07480
  823 ARAT=VO/VW                                                                BPP07490
      IF(GC.GE.0.0) GO TO 824                                                   BPP07500
      IF(GC.LT.0.0) GO TO 825                                                   BPP07510
  824 AKRW=SW*SW*X(J,K+40)                                                      BPP07520
      AKRN=X(J,K+32)*(2.0*SO*ARAT+SO*SO*(1.0-2.0*ARAT))                         BPP07530
      TOT=AKRW/VW+AKRN/VO                                                       BPP07540
      X(J,K+74)=X(J,K+32)*VO*TOT                                                BPP07550
      GO TO 830                                                                 BPP07560
  825 AKRW=X(J,K+40)*(2.0*SW/ARAT+SO*SO*(1.0-2.0/ARAT))                         BPP07570
      AKRN=X(J,K+32)*SO*SO                                                      BPP07580
      TOT=AKRW/VW+AKRN/VO                                                       BPP07590
      X(J,K+74)=TOT*VO*X(J,K+32)                                                BPP07600
  830 CONTINUE                                                                  BPP07610
      X(J,K+74)=ABS(X(J,K+74))                                                  BPP07620
      X(J,K+110)=0.0                                                            BPP07630
      X(J,K+118)=0.0                                                            BPP07640
      X(J,K+84)=0.0                                                             BPP07650
      X(J,83)=0.0                                                               BPP07660
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FORTRAN SOURCE LIST UB 4

SN	SOURCE STATEMENT	
21	X(J,84)=0.0	BPP07640
22	IK=J/JR+1	BPP07650
23	JK=J-JR*(IK-1)	BPP07660
24	IF(JK.LE.0)IK=IK-1	BPP07670
27	IF(JK.LE.0)JK=JR	BPP07680
32	IF(IK.EQ.1)GO TO 140	BPP07690
35	IF(IK.EQ.2.AND.K.EQ.1)GO TO 140	BPP07700
42	IF(IK.EQ.2.AND.K.GE.7)GO TO 140	BPP07710
43	R=GC*((1.0/XA)-(1.0/X(J,K)))	BPP07720
44	R=-R	BPP07730
45	GO TO 150	BPP07740
46	140 R=GC/X(J,K)	BPP07750
47	150 CONTINUE	BPP07760
50	IF(X(J,K+16).EQ.3.0) X(J,K+84)= R	BPP07770
53	IF(X(J,K+16).EQ.3.5) X(J,K+84)=-R	BPP07780
56	78 CONTINUE	BPP07790
60	500 RETURN	BPP07800
61	END	BPP07810

IBMAP ASSEMBLY UB 4

ESSAGES FOR ABOVE ASSEMBLY

FORTRAN SOURCE LIST

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SN        SOURCE STATEMENT
 0  $IBFTCSUB 5                                                          BPP07820
 1        SUBROUTINE CHANGE                                             BPP07830
 2        COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,BPP07840
         1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID              BPP07850
 3        COMMON/CHAN/DIFO,WDIF                                         BPP07860
 4        COMMON/SOLB/CAP(10,10),I,ICHANG,ARAT,TRAP                     BPP07861
 5        COMMON/SOLC/ADD,CP,JIM,ICP                                    BPP07862
 6        DIMENSION B(9),C(8)                                           BPP07870
 7        REAL KA                                                       BPP07880
 8     69 FORMAT(2X,5HDIFO=,E13.5,5X,5HWDIF=,E13.5)                     BPP07890
 1        IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,DIFO,WDIF        BPP07891
 4        IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=17,24) BPP07892
 3        IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=75,82) BPP07893
 2        IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K+94),K=1,32) BPP07894
 1    680 FORMAT(1X,8E15.7)                                             BPP07895
 2        DO 550 K=1,8                                                  BPP07900
   C      SELECT TUBES FOR FLOW CHANGES SO THAT MATERIAL BALANCE FOR EACH PHBPP07910
   C      IS SATISFIED IN EACH NODE OF THE MODEL                        BPP07920
 3        C(K)=0.0                                                      BPP07930
 4    550 CONTINUE                                                      BPP07940
   C      ETTING FLUID IMBIBITION                                       BPP07950
 6        BASE=0.0                                                      BPP07960
 7        KA=0.0                                                        BPP07970
 9        CAT=0.0                                                       BPP07980
 1        ACE=0.0                                                       BPP07981
 2        IF(GC.GE.0.0.AND.WDIF.GT.0.0) KA=1.0                          BPP07990
 5        IF(GC.LT.0.0.AND.DIFO.GT.0.0) KA=2.0                          BPP08000
 0        IF(KA.EQ.0.0)KA=4.5                                           BPP08010
 3        IF(KA.EQ.4.5) CAT=0.3                                         BPP08020
 6    554 B(1)=0.0                                                      BPP08030
 7        DO 555 K=1,8                                                  BPP08040
 0        V=0.0                                                         BPP08050
 1        IF(X(J,K+24).GE.2.0)GO TO 555                                 BPP08060
 4        IF(C(K).NE.0.0) GO TO 555                                     BPP08070
 7        IF(FLO(J,K).NE.KA) GO TO 555                                  BPP08080
 2        IF(AP(J,K).LE.0.0) GO TO 555                                  BPP08081
 5        V=AP(J,K)*X(J,K+74)                                           BPP08090
 6        V=ABS(V)                                                      BPP08100
 7    555 B(K+1)=B(K)+V                                                 BPP08110
 1    556 CONTINUE                                                      BPP08120
 2        IF(B(9).EQ.0.0) GO TO 559                                     BPP08130
 5        RN=RNDY1(0.)                                                  BPP08140
 6        DO 557 K=2,9                                                  BPP08150
 7        IF(RN.LE.B(K)/B(9)) GO TO 558                                 BPP08160
 2    557 CONTINUE                                                      BPP08170
 4    558 K=K-1                                                         BPP08180
 5        C(K)=1.0                                                      BPP08190
 6        GO TO 570                                                     BPP08200
   C      PENDULAR FLOW CHANGE                                          BPP08210
 7    559 IF(CAT.GE.0.3) GO TO 560                                      BPP08220
 2        KA=4.5                                                        BPP08230
 3        CAT=0.3                                                       BPP08240
 4        GO TO 554                                                     BPP08250
 5    560 IF(CAT.EQ.0.3) GO TO 561                                      BPP08260
 0        IF(CAT.EQ.0.4) GO TO 562                                      BPP08270
```

FORTRAN SOURCE LIST UB 5

SOURCE STATEMENT

```
      IF(CAT.EQ.0.5) GO TO 563                                          BPP08280
      IF(CAT.EQ.0.6) GO TO 564                                          BPP08281
      IF(CAT.EQ.0.8)GO TO 565                                           BPP08282
      GO TO 620                                                         BPP08290
  561 CONTINUE                                                          BPP08300
C     SLUG FLOW CHANGE                                                  BPP08310
      IF(WDIF.GT.0.0)KA=4.2                                             BPP08320
      IF(DIFO.GT.0.0) KA=4.2                                            BPP08330
      CAT=0.4                                                           BPP08340
      GO TO 554                                                         BPP08350
  565 IF(WDIF.GT.0.0)KA=4.1                                             BPP08360
      IF(DIFO.GT.0.0)KA=4.1                                             BPP08362
      CAT=0.8                                                           BPP08363
      GO TO 554                                                         BPP08364
  562 CONTINUE                                                          BPP08365
C     DISPLACEMENT FLOW CHANGE                                          BPP08370
      IF(DIFO.GT.0.0) KA=3.0                                            BPP08380
      IF(WDIF.GT.0.0) KA=3.5                                            BPP08390
      CAT=0.5                                                           BPP08400
      GO TO 554                                                         BPP08410
  563 CONTINUE                                                          BPP08420
C     NON WETTING FLUID IMBIBITION                                      BPP08430
      KA=0.0                                                            BPP08440
      IF(DIFO.GT.0.0)KA=2.0                                             BPP08450
      IF(WDIF.GT.0.0)KA=1.0                                             BPP08460
      CAT=0.6                                                           BPP08470
      GO TO 554                                                         BPP08480
  564 CONTINUE                                                          BPP08491
      IF(WDIF.GT.0.0)KA=3.0                                             BPP08492
      IF(DIFO.GT.0.0)KA=3.5                                             BPP08493
      CAT=0.7                                                           BPP08494
      IF(KA.EQ.0.0)GO TO 620                                            BPP08495
      GO TO 554                                                         BPP08496
  570 V=AP(J,K)*X(J,K+74)*TIME                                          BPP08500
      FLO(J,K)=KA                                                       BPP08510
      IF(KA.EQ.3.0)FLO(J,K)=3.0                                         BPP08520
      IF(KA.EQ.3.5)FLO(J,K)=3.5                                         BPP08530
      IF(KA.EQ.4.1)FLO(J,K)=4.1                                         BPP08540
      IF(KA.EQ.4.2)FLO(J,K)=4.2                                         BPP08550
      IF(KA.EQ.1.0) FLO(J,K)=3.0                                        BPP08560
      IF(KA.EQ.2.0) FLO(J,K)=3.5                                        BPP08570
      IF(CAT.EQ.0.5)FLO(J,K)=4.5                                        BPP08571
      VOMAX=X(J,K+48)                                                   BPP08580
      VOMIN=0.0                                                         BPP08590
      IF(GC.LT.0.0) VOMIN=0.04*VOMAX                                    BPP08600
      IF(GC.GE.0.0) VOMAX=0.96*VOMAX                                    BPP08610
      IF(X(J,K+56).GT.VOMAX) VOMAX=X(J,K+48)                            BPP08620
      IF(X(J,K+56).LT.VOMIN) VOMIN=0.0                                  BPP08630
      VWMAX=X(J,K+48)-VOMIN                                             BPP08640
      VWMIN=X(J,K+48)-VOMAX                                             BPP08650
      VOLO=VOMAX-X(J,K+56)                                              BPP08660
      VOLW=X(J,K+56)-VOMIN                                              BPP08670
      CASE=0.0                                                          BPP08680
      IF(DIFO.GT.0.0) V=X(J,K+102)                                      BPP08690
      IF(WDIF.GT.0.0) V=X(J,K+94)                                       BPP08700
```

FORTRAN SOURCE LIST UB 5

```
      SOURCE STATEMENT

      IF(WDIF.GT.0.0) GO TO 601                                          BPP08710
      IF(DIFO.GT.0.0) GO TO 603                                          BPP08720
C     WATER EXCESS                                                       BPP08730
  601 IF(V.GT.WDIF) GO TO 602                                            BPP08740
      WDIF=WDIF-V                                                        BPP08750
      X(J,K+94)=0.0                                                      BPP08760
      X(J,K+102)=X(J,K+102)+V                                            BPP08770
      IF(V.LT.VOLW) GO TO 12                                             BPP08780
      FLO(J,K)=2.0                                                       BPP08790
      VOF(J,K)=VOMIN                                                     BPP08800
      GO TO 554                                                          BPP08810
   11 VOF(J,K)=X(J,K+56)-V                                               BPP08820
      GO TO 12                                                           BPP08830
  602 VOF(J,K)=VOMIN                                                     BPP08840
      IF(VOLW.GT.WDIF) VOF(J,K)=X(J,K+56)-WDIF                           BPP08850
      IF(VOLW.LT.WDIF) FLO(J,K)=2.0                                      BPP08860
      IF(GC.LT.0.0.AND.FLO(J,K).EQ.2.0) FLO(J,K)=4.5                     BPP08870
      X(J,K+94)=X(J,K+94)-WDIF                                           BPP08880
      X(J,K+102)=X(J,K+102)+WDIF                                         BPP08890
      WDIF=0.0                                                           BPP08900
   12 CONTINUE                                                           BPP08910
      SO=VOF(J,K)/X(J,K+48)                                              BPP08920
      IF(FLO(J,K).EQ. 4.5.AND.GC.GT.0.0) CASE=0.5                        BPP08930
      IF(CASE.EQ.0.5.AND.SO.LT.0.80)FLO(J,K)=4.1                         BPP08940
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.4.1) BASE=1.0                    BPP08950
      IF(BASE.EQ.1.0.AND.GC.GE.0.0) CASE=1.0                             BPP08960
      IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=2.0                             BPP08970
      IF(CASE.EQ.1.0.AND.SO.GE.0.8) FLO(J,K)=4.5                         BPP08980
      IF(CASE.EQ.2.0.AND.SO.LE.0.2) FLO(J,K)=4.5                         BPP08990
      CASE=0.0                                                           BPP09000
      BASE=0.0                                                           BPP09010
      IF(WDIF.NE.0.0)GO TO 554                                           BPP09020
      GO TO 590                                                          BPP09030
C     OIL EXCESS                                                         BPP09040
  603 IF(V.GT.DIFO) GO TO 604                                            BPP09050
      DIFO=DIFO-V                                                        BPP09060
      X(J,K+94)=X(J,K+94)+V                                              BPP09070
      X(J,K+102)=0.0                                                     BPP09080
      IF(V.LT.VOLO) GO TO 13                                             BPP09090
      VOF(J,K)=VOMAX                                                     BPP09100
      FLO(J,K)=1.0                                                       BPP09110
      IF(GC.GT.0.0) FLO(J,K)=4.5                                         BPP09120
      GO TO 554                                                          BPP09130
   13 VOF(J,K)=X(J,K+56)+V                                               BPP09140
      GO TO 14                                                           BPP09150
  604 VOF(J,K)=VOMAX                                                     BPP09160
      IF(VOLO.GT.DIFO) VOF(J,K)=X(J,K+56)+DIFO                           BPP09170
      IF(VOLO.LT.DIFO) FLO(J,K)=1.0                                      BPP09180
      IF(GC.GE.0.0.AND.FLO(J,K).EQ.1.0) FLO(J,K)=4.5                     BPP09190
      X(J,K+102)=X(J,K+102)-DIFO                                         BPP09200
      X(J,K+94)=X(J,K+94)+DIFO                                           BPP09210
      DIFO=0.0                                                           BPP09220
   14 CONTINUE                                                           BPP09230
      SO=VOF(J,K)/X(J,K+48)                                              BPP09240
      IF(FLO(J,K).EQ.4.5.AND.GC.LE.0.0)CASE=0.5                          BPP09250
```

FORTRAN SOURCE LIST UB 5 12/

SOURCE STATEMENT

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      IF(CASE.EQ.0.5.AND.SO.GT.0.2)FLO(J,K)=4.2                          BPP09270
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.4.1)BASE=1.0                     BPP09280
      IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=1.0                             BPP09290
      IF(BASE.EQ.1.0.AND.GC.GE.0.0)CASE=2.0                              BPP09300
      IF(CASE.EQ.1.0.AND.SO.LE.0.2) FLO(J,K)=4.5                         BPP09310
      IF(CASE.EQ.2.0.AND.SO.GE.0.8) FLO(J,K)=4.5                         BPP09320
      BASE=0.0                                                           BPP09330
      CASE=0.0                                                           BPP09340
      IF(DIFO.NE.0.0) GO TO 554                                          BPP09350
  590 CONTINUE                                                           BPP09360
  620 IF(DIFO.LE.0.1E-10)DIFO=0.0                                        BPP09370
      IF(WDIF.LE.0.1E-10)WDIF=0.0                                        BPP09380
      IF(DIFO.EQ.0.0.AND.WDIF.EQ.0.0)GO TO 630                           BPP09381
      ACE=ACE+1.0                                                        BPP09382
      DO 35 K=1,8                                                        BPP09383
   35 C(K)=0.0                                                           BPP09384
      CAT=0.3                                                            BPP09385
      KA=4.5                                                             BPP09386
      IF(ACE.EQ.1.0)GO TO 554                                            BPP09387
  630 IF(WDIF.NE.0.0.OR.DIFO.NE.0.0)PRINT690,DIFO,WDIF                   BPP09390
      RETURN                                                             BPP09400
      END                                                                BPP09410
```

FORTRAN PROGRAM UB 5 12/

FUNCTION SUBPROGRAM REFERENCES

IBMAP ASSEMBLY UB 5 12/

ESSAGES FOR ABOVE ASSEMBLY

FORTRAN SOURCE LIST

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    SOURCE STATEMENT

.IBFTCSUB 6                                                                    BPP0942
      SUBROUTINE PDIF                                                          BPP0943
      COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,BPP0944
     1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID                        BPP0945
       FILL PRESS DIFFERENTIALS FOR ALL TUBES AT EACH NODE POINT               BPP0946
      J=IJ                                                                     BPP0947
      IK=IJ/JR+1                                                               BPP0948
      JK= IJ-JR*(IK-1)                                                         BPP0949
      IF(JK.LE.1)IK=IK-1                                                       BPP0950
      IF(JK.LE.1)JK=JR                                                         BPP0951
   35 FORMAT(1X,2I3)                                                           BPP0952
      X(J,74)=EP(IK,JK)                                                        BPP0953
      IF(IK.EQ.1)GO TO 87                                                      BPP0954
      IF(JK.EQ.1)GO TO 92                                                      BPP0955
      IF(IK.EQ.IR) GO TO 96                                                    BPP0956
      IF(JK.EQ.JR) GO TO 100                                                   BPP0957
      X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)                                          BPP0958
      X(J,66)=EP(IK,JK)-EP(IK,JK+1)                                            BPP0959
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)                                          BPP0960
      X(J,68)=EP(IK,JK)-EP(IK+1,JK)                                            BPP0961
      X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)                                          BPP0962
      X(J,70)=EP(IK,JK)-EP(IK,JK-1)                                            BPP0963
      X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)                                          BPP0964
      X(J,72)=EP(IK,JK)-EP(IK-1,JK)                                            BPP0965
      GO TO 102                                                                BPP0966
   87 IF(JK.EQ.1) GO TO 88                                                     BPP0967
      IF(JK.EQ.JR) GO TO 90                                                    BPP0968
      X(J,65)=0.0                                                              BPP0969
      X(J,66)=0.0                                                              BPP0970
      X(J,70)=0.0                                                              BPP0971
      X(J,71)=0.0                                                              BPP0972
      X(J, 72)=0.0                                                             BPP0973
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)                                          BPP0974
      X(J,68)=EP(IK,JK)-EP(IK+1,JK)                                            BPP0975
      X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)                                          BPP0976
      GO TO 102                                                                BPP0977
   88 X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)                                          BPP0978
      DO 89 K=1,8                                                              BPP0979
      IF(K.EQ.3) GO TO 89                                                      BPP0980
      X(J,K+64)=0.0                                                            BPP0981
   89 CONTINUE                                                                 BPP0982
      GO TO 102                                                                BPP0983
   90 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)                                          BPP0984
      DO 91 K=1,8                                                              BPP0985
      IF(K.EQ.5) GO TO 91                                                      BPP0986
      X(J,K+64)=0.0                                                            BPP0987
   91 CONTINUE                                                                 BPP0988
      GO TO 102                                                                BPP0989
   92 IF(IK.EQ.IR) GO TO 94                                                    BPP0990
      X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)                                          BPP0991
      X(J,66)=EP(IK,JK)-EP(IK,JK+1)                                            BPP0992
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)                                          BPP0993
      DO 93 K=4,8                                                              BPP0994
      X(J,K+64)=0.0                                                            BPP0995
   93 CONTINUE                                                                 BPP0996
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FORTRAN SOURCE LIST UB 6

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SN        SOURCE STATEMENT                                                    
16            GO TO 102                                                       BPP09970
17         94 X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)                                 BPP09980
20            DO 95 K=2,8                                                     BPP09990
21            X(J,K+64)=0.0                                                   BPP10000
22         95 CONTINUE                                                        BPP10010
24            GO TO 102                                                       BPP10020
25         96 IF(JK.EQ.JR) GO TO 98                                           BPP10030
30            X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)                                 BPP10040
31            X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)                                 BPP10050
32            X(J,72)=EP(IK,JK)-EP(IK-1,JK)                                   BPP10060
33            DO 97 K=2,6                                                     BPP10070
34            X(J,K+64)=0.0                                                   BPP10080
35         97 CONTINUE                                                        BPP10090
37            GO TO 102                                                       BPP10100
40         98 X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)                                 BPP10110
41            DO 99 K=1,8                                                     BPP10120
42            IF(K.EQ.7)GO TO 99                                              BPP10130
45            X(J,K+64)=0.0                                                   BPP10140
46         99 CONTINUE                                                        BPP10150
50            GO TO 102                                                       BPP10160
51        100 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)                                 BPP10170
52            X(J,70)=EP(IK,JK)-EP(IK,JK-1)                                   BPP10180
53            X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)                                 BPP10190
54            X(J,72)=0.0                                                     BPP10200
55            DO 101 K=1,4                                                    BPP10210
56            X(J,K+64)=0.0                                                   BPP10220
57        101 CONTINUE                                                        BPP10230
61        102 CONTINUE                                                        BPP10240
    C         FILL POSITIVE DIFFERENTIAL PR. AND CAP. PR.                     BPP10250
62            DO 104 K=1,8                                                    BPP10260
63            VOF(J,K)=0.0                                                    BPP10270
64            AP(J,K)=0.0                                                     BPP10280
65            IF(X(J,K).EQ.0.0) GO TO 104                                     BPP10290
70            X(J,K+64)=X(J,K+64)+X(J, K+84)                                  BPP10300
71            IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)                           BPP10310
74        104 CONTINUE                                                        BPP10320
76            RETURN                                                          BPP10330
77            END                                                             BPP10340
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IBMAP ASSEMBLY UB 6

ESSAGES FOR ABOVE ASSEMBLY

FORTRAN SOURCE LIST

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      SOURCE STATEMENT

$IBFTCSUB 7                                                                BPP10850
      SUBROUTINE SIMU                                                      BPP10860
C     PROGRAM SIMU                                                         BPP10870
      COMMON/SYMARG/X(50,16 ),AP(50,8),GC,VD,VW,TIME,VOF(50,8),IJ,IR,JR,BPP10880
     1XA    ,EP(50,20),HYST,CAT,GAMMA,J,FLO(50,8),GRID                    BPP10890
      COMMON/SOLC/AOD,CP,JIM,ICP                                           BPP10900
      COMMON/SIM/COM(25),RAD(25),KL,LK                                     BPP10910
      DIMENSION B(50,8)                                                    BPP10920
      FACT=5.9473E-3*2.65/1.782                                            BPP10930
      DO 50 J=1,JR                                                         BPP10940
      DO 6  I=1,IR                                                         BPP10950
      ISK=(I-1)*JR+J                                                       BPP10960
      DO 20 M=1,8                                                          BPP10970
      X(ISK,M+8)=1.0                                                       BPP10980
      X(ISK,M+16)=1.0                                                      BPP10990
      X(ISK,M+24)=1.0                                                      BPP11000
      X(ISK,M+32)=1.0                                                      BPP11010
      X(ISK,M+40)=1.0                                                      BPP11020
      X(ISK,M+48)=1.0                                                      BPP11030
      X(ISK,M+56)=1.0                                                      BPP11040
      X(ISK,M+64)=1.0                                                      BPP11050
   20 CONTINUE                                                             BPP11060
      X(ISK,73)=1.                                                         BPP11070
      X(ISK,74)=1.0                                                        BPP11080
      IF(J.EQ.JR) GO TO 120                                                BPP11090
      DO 70 K=1,4                                                          BPP11100
      RN=RNDY1(Y)                                                          BPP11110
      DO 75 M=1,LK                                                         BPP11120
      IF(RN.LE.COM(M)) GO TO 100                                           BPP11130
   75 CONTINUE                                                             BPP11140
  100 X(ISK,K)=RAD(M)                                                      BPP11150
   70 CONTINUE                                                             BPP11160
      GO TO 130                                                            BPP11170
  120 DO 160 K=1,4                                                         BPP11180
      X(ISK,8)=0.0                                                         BPP11190
  160 CONTINUE                                                             BPP11200
      X(ISK,5)=0.0                                                         BPP11210
  130 IF(J.NE.1) GO TO 150                                                 BPP11220
      DO 165 K=4,8                                                         BPP11230
      X(ISK,K)=0.0                                                         BPP11240
  165 CONTINUE                                                             BPP11250
  150 IF(I.NE.1) GO TO 155                                                 BPP11260
      X(ISK,1)=0.0                                                         BPP11270
      X(ISK,2)=0.0                                                         BPP11280
      X(ISK,6)=0.0                                                         BPP11290
      X(ISK,7)=0.0                                                         BPP11300
      X(ISK,8)=0.0                                                         BPP11310
  155 IF(I.NE.IR) GO TO 180                                                BPP11320
      DO 195 K=2,6                                                         BPP11330
      X(ISK,K)=0.0                                                         BPP11340
  195 CONTINUE                                                             BPP11350
C     FILL ALL TUBE RADII                                                  BPP11360
  180 IF(J.EQ.1)  GO TO 190                                                BPP11370
      DO 135 N=1,3                                                         BPP11380
      IF(I.EQ.1.AND.N.NE.1) GO TO 135                                      BPP11390
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FORTRAN SOURCE LIST UB 7

SOURCE STATEMENT

```
      IF(I.EQ.IR.AND.N.NE.3) GO TO 135                                  BPP10900
      IP=I-N+2                                                          BPP10910
      IS=(IP-1)*JR+J-1                                                  BPP10920
      X(ISK,N+4)=X(IS,N)                                                BPP10930
  135 CONTINUE                                                          BPP10940
      IF(I.EQ.1) GO TO 190                                              BPP10950
      IS=(I-2)*JR+J                                                     BPP10960
      X(ISK,8)=X(IS,4)                                                  BPP10970
  190 CONTINUE                                                          BPP10980
C     FILL LENGTH IN 9-16                                               BPP10990
      DO 230 K=9,16                                                     BPP11000
      X(ISK,9)=1.4142                                                   BPP11010
      IF(X(ISK,K-1).EQ.1.0) X(ISK,K)=1.4142                             BPP11020
  230 CONTINUE                                                          BPP11030
C     FILL OIL AND WATER CONDUCTIVITIES IN 33-40AND41-48RESPECTIVELY     BPP11040
      DO 300 K=1,8                                                      BPP11050
      X(ISK,K+8)=X(ISK,K+8)*GRID                                        BPP11060
      B(ISK,K)=(FACT*X(ISK,K)**4)/X(ISK,K+8)                            BPP11070
      X(ISK,K+32)=B(ISK,K)/VO                                           BPP11080
      X(ISK,K+40)=B(ISK,K)/VW                                           BPP11090
C     COMPUTE VOLUMES OF TUBES                                          BPP11100
      X(ISK,K+48)=3.0*1.732*X(ISK,K+8)*X(ISK,K)**2.0                    BPP11110
C     FILL FLOW OF OIL IN ALL TUBES 75-64                               BPP11120
      X(ISK,K+56)=X(ISK,K+48)                                           BPP11130
      X(ISK,K+74)=X(ISK,K+32)                                           BPP11140
      X(ISK,K+84)=0.0                                                   BPP11150
      X(ISK,K+94)=0.0                                                   BPP11160
      X(ISK,K+102)=0.0                                                  BPP11170
      X(ISK,K+110)=0.0                                                  BPP11180
      X(ISK,K+118)=0.0                                                  BPP11190
      X(ISK,K+128)=0.0                                                  BPP11200
      X(ISK,K+136)=0.0                                                  BPP11210
      X(ISK,K+144)=0.0                                                  BPP11220
      X(ISK,K+152)=0.0                                                  BPP11230
      IF(X(ISK,K).EQ.0.0) X(ISK,K+24)=2.0                               BPP11240
  300 CONTINUE                                                          BPP11250
      X(ISK,82)=0.0                                                     BPP11260
      X(ISK,84)=0.0                                                     BPP11270
      X(ISK,92)=0.0                                                     BPP11280
      X(ISK,94)=0.0                                                     BPP11290
      X(ISK,127)=0.0                                                    BPP11300
      X(ISK,128)=0.0                                                    BPP11310
C     ASSIGN VALUES TO DEL PR IN 65-72                                  BPP11320
      IAN=IR-1                                                          BPP11330
      AN=IAN                                                            BPP11340
      Z=CP/AN                                                           BPP11350
      DO 301 K=3,5                                                      BPP11360
      X(ISK,K+64)=Z                                                     BPP11370
  301 CONTINUE                                                          BPP11380
      X(ISK,71)=-Z                                                      BPP11390
      X(ISK,72)=-Z                                                      BPP11400
      X(ISK,65)=-Z                                                      BPP11410
      X(ISK,66)=0.0                                                     BPP11420
      X(ISK,70)=0.0                                                     BPP11430
C     ASSIGN PRESSURE 74                                                BPP11440
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FORTRAN SOURCE LIST UB 7

```
SN        SOURCE STATEMENT

)5          Y=I
)6          YS=IR
)7          X(ISK,74)=CP*(YS-Y)/(YS-1.0)
)0          IJ=(I-1)*JR+J
.1        1 FORMAT(5X,8E15.7)
.2       60 CONTINUE
)4       50 CONTINUE
.6          RETURN
.7          END
```

FORTRAN PROGRAM UB 7

FUNCTION SUBPROGRAM REFERENCES

IBMAP ASSEMBLY UB 7

ESSAGES FOR ABOVE ASSEMBLY

IBLDR -- JOB

*** OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT 08 HRS. 32 MTS. 02 SECS